TARDEC

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Computer Generated Root-Mean-Square (RMS) Roughness Courses for Ride Quality Evaluation

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Power Spectral Density descriptions of each surface profile were used with digital simulation of stationary random processes to generate distance histories. Theoretical foundations and background on random processes and analysis of them are referenced.

For the specific example of surface profiles the mathematical preliminaries demonstrated the particular analytical techniques necessary to simulate random processes and apply it to surface profiles. In our examples the surface profile description was a one sided power spectral density function with defined constant slope frequency domain.

With the ability to simulate surface profiles and the -2 (log scale) slope description restriction the constant was determined relating the surface roughness parameter, RMS, to the PSD surface profile description, allowing for the generation of a set of courses to simulate any desired level of surface roughness

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2. INTRODUCTION

One of the driving forces in evaluating vehicle dynamics is the surface profile. Simulations of vehicle dynamics are used to predict system performance based on human tolerance limits to vibration levels over a specified roughness course.

Descriptions of surface profiles have been presented in Van Deusen (1967), Dodds and Robson (1973), Healey et.al. (1977). A generalized case for relating random processes to surface profiles is addressed in Shinozuka (1971).

Computer generation of these RMS roughness courses is based on the simulation of stationary random processes, by which the designer can define the type of surface profile desired through frequency content and generate a time series.

2.1 Random Processes

Random processes are used to mathematically represent a surface profile since naturally occurring surfaces are not predefined and depending on the current geographical area do have variability in them. Naturally occurring phenomenon and environmental conditions, such as rain, wind, snow, and temperature fluctuations cause changes to occur. For in-depth coverage of random processes Papoulis (1984) is highly recommended.

2.2 Power Spectral Density

To generate roughness courses the fundamental relationship between the Power Spectral Density (PSD) function, $S_g(w)$, and the distance domain, $g(x)$, needs to be found where the PSD is the Fourier Transform of the auto-correlation function

$$S_g(w) = \frac{1}{2\pi}\int_{-\infty}^{+\infty} R_g(\tau)e^{-jw\tau}\,d\tau \tag{1}$$

and the auto-correlation function can be gotten from the PSD through the inverse Fourier Transform

$$R_g(\tau) = \int_{-\infty}^{+\infty} S_g(w)e^{jw\tau}\,dw \tag{2}$$

where

$$R_g(\tau) = E\left[g(x+\tau)g^*(x)\right] \tag{3}$$

with $E[\;]$ being defined as the standard expectation operator. For real-valued random processes the auto-correlation function is even which reduces the PSD to

$$S_g(w) = \int_{-\infty}^{+\infty} R_g(\tau)\cos(w\tau)d\tau\,. \tag{4}$$

giving a real-valued, even PSD of w.

2.3 Random Process Simulation

Simulation of the random process requires the use of the relationship between the surface profile function $g(x)$ and the PSD function $S_g(w)$. The forward operation

$$g(x) \to S_g(w) \tag{5}$$

known as the PSD is defined in (1). Proakis and Manolakis (1988) discuss many well known methods for calculating PSD's. Less obvious is the reverse operation

$$S_g(w) \to g(x)\,. \tag{6}$$

The difficulty lies in that $g(x)$ is in terms of the auto-correlation function. A direct extraction of $g(x)$ from $R_g(\tau)$ is problematic.

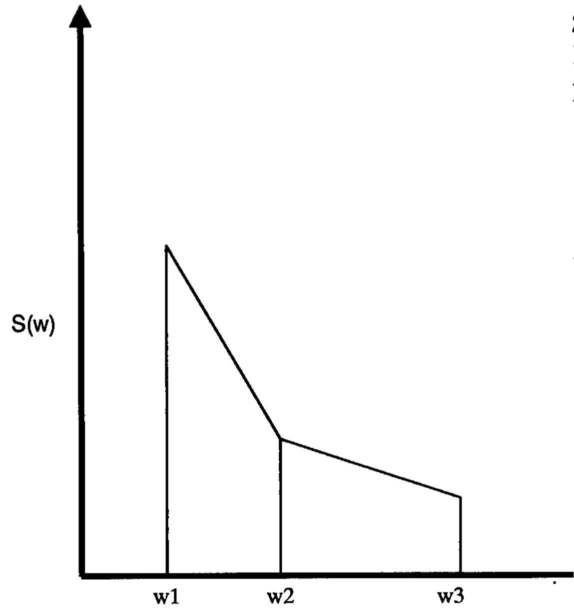


Figure 1 - Example Power Spectral Density function

From (2) and (3) the expected value relates the distance function to the PSD identifying a relationship that will satisfy (6). Through the use of trigonometric identities and conveniently chosen probability distributions Shinozuka and Jan (1972) determined the relationship to be

$$g(x) = \sqrt{2}\sum_{k=1}^{N} \sqrt{S_g(w_k)\Delta w_k}\cos(w'_k x + \phi_k) \tag{7}$$

where ϕ is a random phase angle uniformly distributed between 0 and 2π,

$\Delta w_k = \dfrac{w_{upper} - w_{lower}}{N}$ with $w_{wpper} = w_3$ and

$w_{lower} = w_1$ as depicted in Figure 1,

$w_k = w_{lower} + (k - 0.5)\Delta w_k$, and

$w'_k = w_k + \delta w$ where δw is uniformly distributed

between $\dfrac{-\Delta w'_k}{2}$ and $\dfrac{+\Delta w'_k}{2}$ where

$\Delta w'_k << \Delta w_k$ to avoid periodicity.

Equation (7) assumes a zero mean, both in ensemble average and temporal mean. Shinozuka and Jan (1972) detail the theoretical basis for these requirements and show the applicability of this method to the multi-dimensional case.

2.4 Generation of Surface Profiles

It is generally accepted that the PSD of a surface profile can be represented as

$$S_g(w) = \begin{Bmatrix} c_1 w^{-n_1}, & w_1 \le w < w_2 \\ c_2 w^{-n_2}, & w_2 \le w < w_3 \end{Bmatrix} \tag{8}$$

as shown in Figure 1.

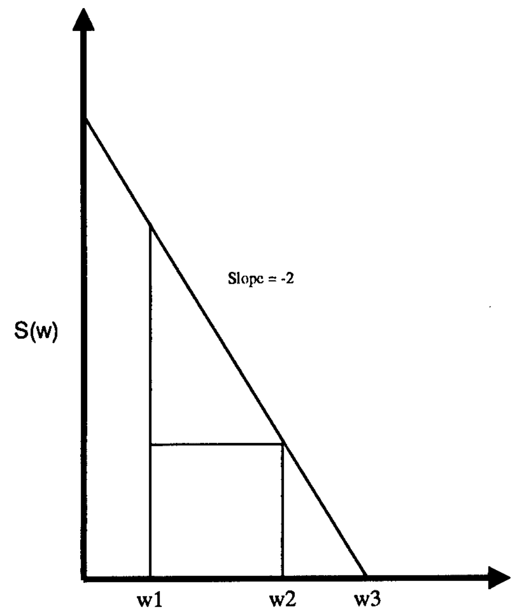


Figure 2 - Example Power Spectral Density function with constant -2 slope

As noted by Sevin and Pilkey (1971) most surfaces can be approximated by

$$S_g(w) = cw^{-2}, \ w_1 \le w < w_3 \tag{9}$$

alone. For this special case note the logarithmic plot is

$$\log(S_g(w)) = -2\log(w) + \log(c) \tag{10}$$

which produces a straight line with slope of -2 as shown in Figure 2.

Further, Parseval's Theorem states that the variance of $g(x)$ is the area under $S_g(w)$. An often used measure of surface roughness is the root-mean-square (RMS) value

$$\text{RMS}=\sqrt{\frac{1}{L}\int_0^L g(x)^2\,dx}=\sigma \tag{11}$$

which is the standard deviation, σ , or the square-root of the variance for zero-mean $g(x)$. Given the -2 slope assumption in (10) and using Parseval's Theorem c is directly related to RMS by

$$c=(RMS)^2\frac{w_1 w_2}{(w_2-w_1)}. \tag{12}$$

For various levels of RMS roughness the corresponding c can be found and used to define the PSD from Figure 2 which, when simulated, will produce a course with the desired roughness.

The more general case in (8) adds flexibility to the surface profile description of the PSD which it estimates, although it has been found that (9) can give a good approximation to the PSD within a band of +/- 3dB.

Ashmore and Piersol (1997) have determined surface profiles based on the definition in (9) for military and commercial roads.

3. RESULTS

The following pages show figures of the generated surface profiles from 0.10 to 5.00 inch RMS in 0.1 increments. Each is 1000 feet with 3 inch samples (4000 points). Each contains the PSD plot with original surface profile description, $S_g(w)$, between +/- 3dB bands and circle points of the PSD generated from $g(x)$ in the first pane. The second pane is a sectional plot of $g(x)$, with the third pane containing a histogram of the full signal. Dimensional units are not included with the plots but are in $\frac{ft^2}{1/ft}$ for $S_g(w)$ and ft for $g(x)$. The shape of the histogram should be noted as that of a Gaussian distribution, with parameters of $\mu=0$, the mean, and σ , the standard deviation. This should not be surprising since the Central Limit Theorem of random variables applies from the summation in (7). Increased RMS levels are also shown by the spread out histogram which corresponds to greater σ since the area of $S_g(w)$ is related to RMS through Parseval's Theorem.

For each RMS level (0.10 - 5.00 inches in 0.1 increments) ten surface profiles $g(x)$ were generated. Figures 3-52 show only one of these for each RMS level. Figures 53-102 are plots of each profile in its entirety with units of inches versus feet. Figures 103-105 show the comparative RMS level between 1.00, 3.00, and 5.00 inch RMS courses all plotted on the same scale (-20 to 20 inches). For reasons of brevity, an example listing of the surface profile (5.00) file is included for reference purposes. Each file is in American Standard Code for Information Interchange (ASCII) with the following format:

```
---BOF---
label
length (points), spacing (inches)
elevation point #0 (inches)
elevation point #1 (inches)
.
.
.
---EOF---
```

Below is a specific example.

```
---BOF---
RMS ROUGHENESS COURSE 1
4000, 3.0
0.0123
0.1236
-0.0900
.
.
.
---EOF---
```

For each elevation point the distance is point#*spacing (starting at zero).

3.1 RMS Course PSD's

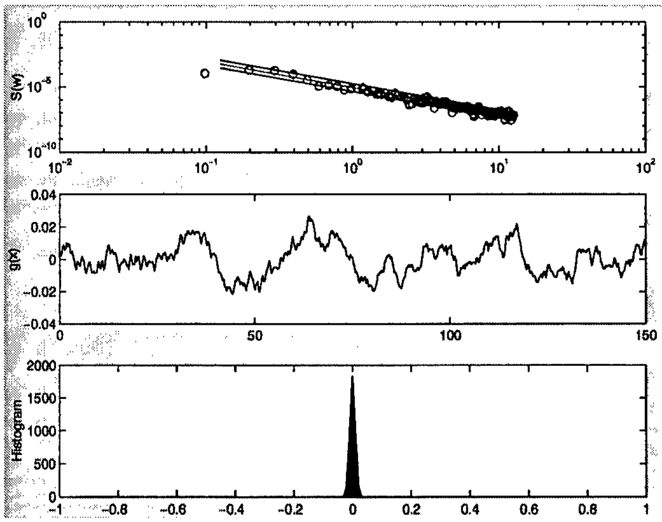


Figure 3 - 0.10" RMS

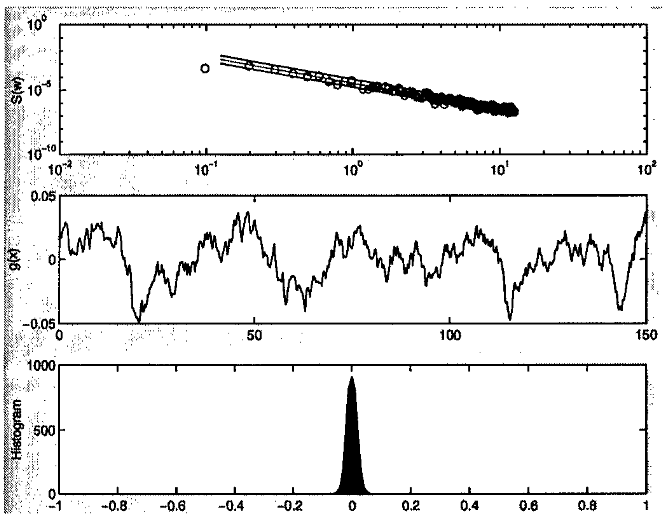


Figure 4 - 0.20" RMS

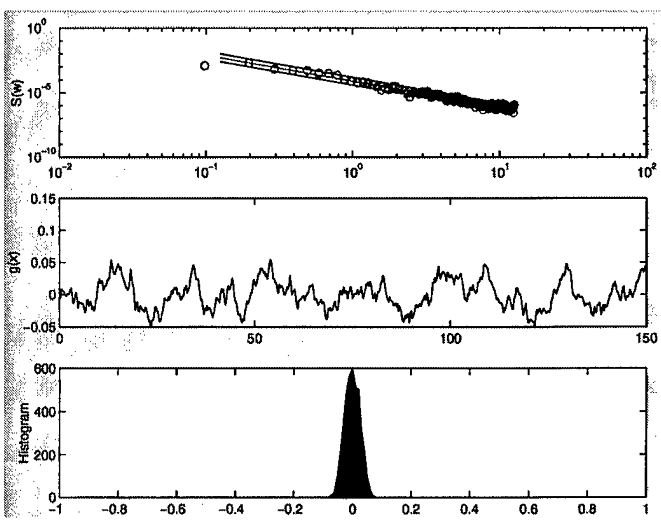


Figure 5 - 0.30" RMS

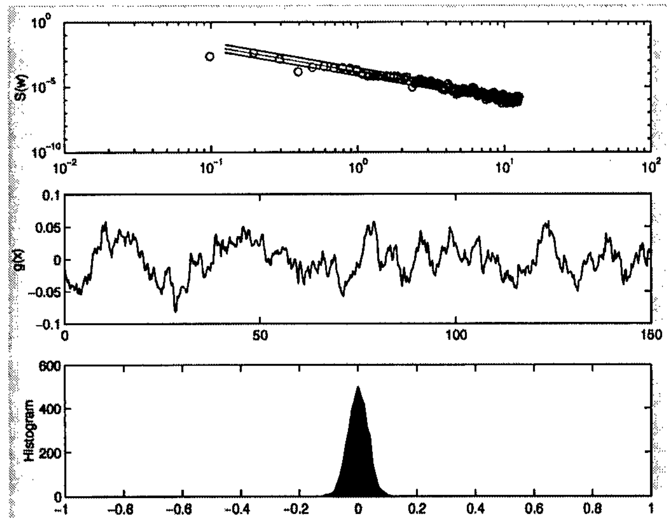


Figure 6 - 0.40" RMS

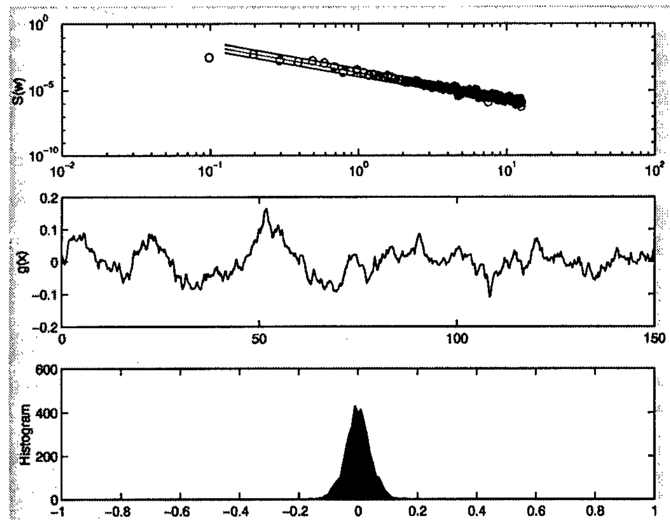


Figure 7 - 0.50" RMS

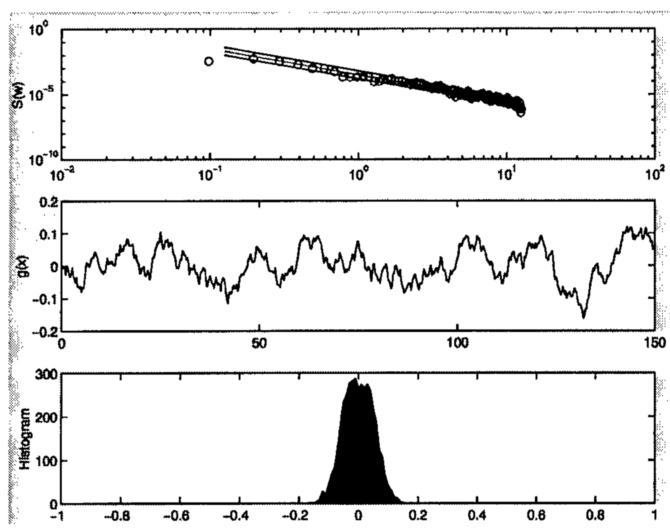


Figure 8 - 0.60" RMS

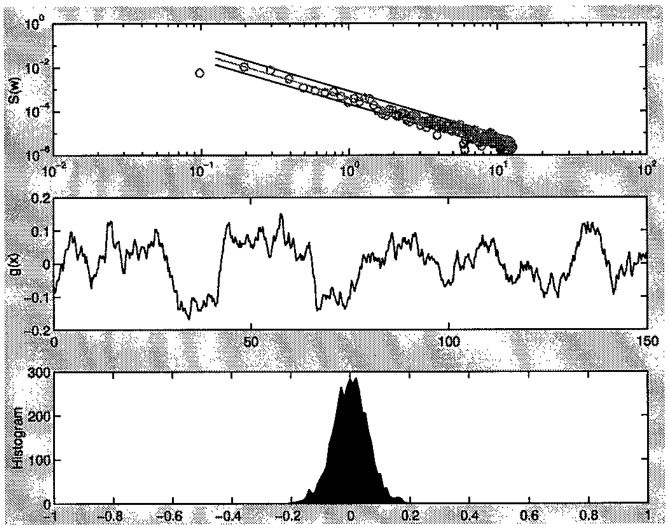


Figure 9 - 0.70" RMS

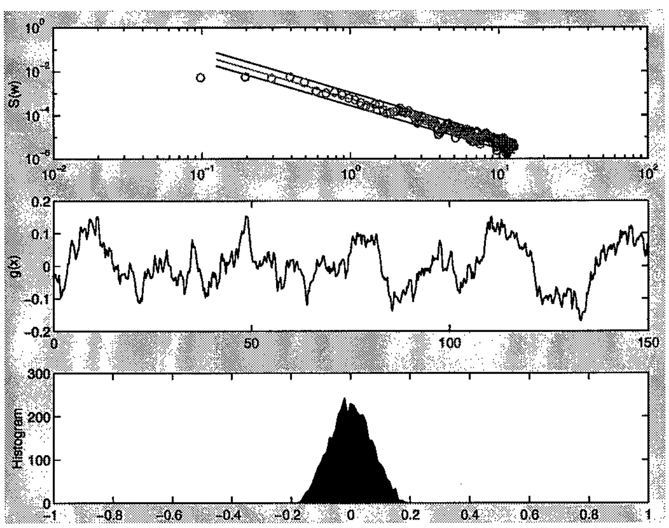


Figure 10 - 0.80" RMS

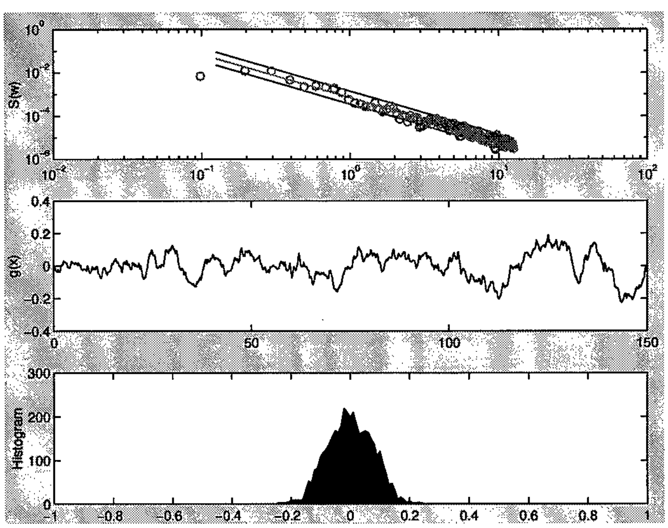


Figure 11 - 0.90" RMS

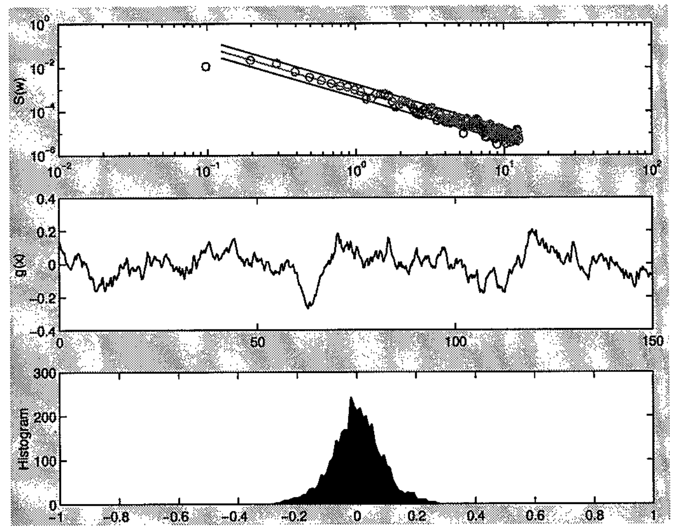


Figure 12 - 1.00" RMS

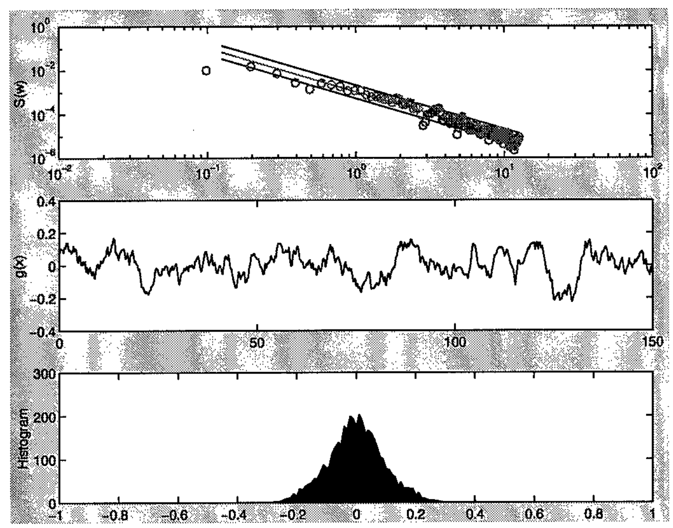


Figure 13 - 1.10" RMS

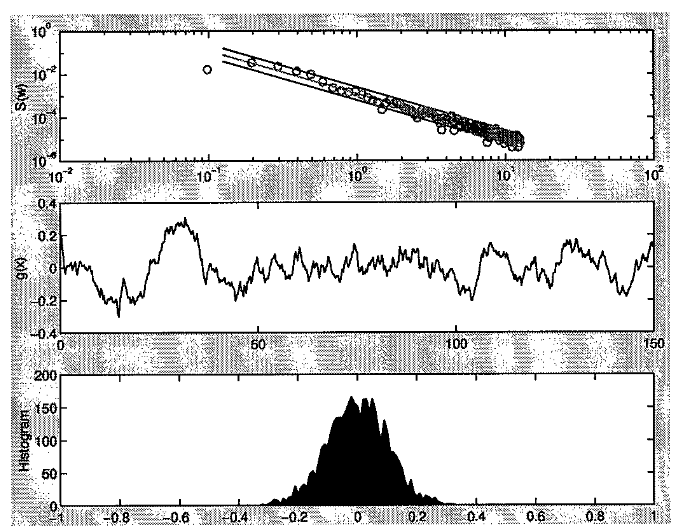
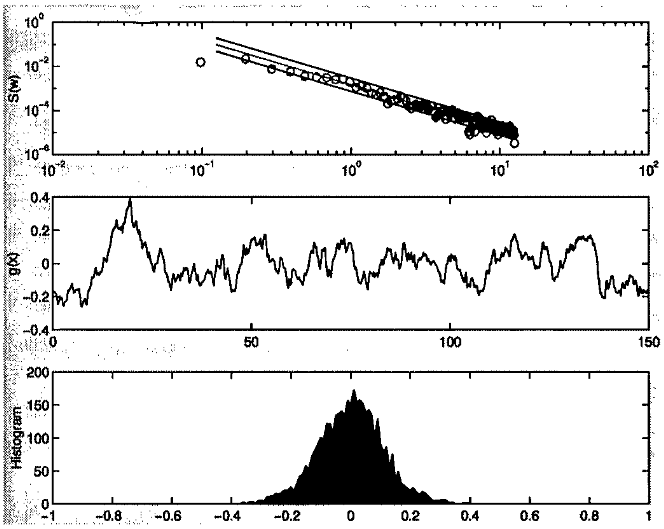


Figure 14 - 1.20" RMS



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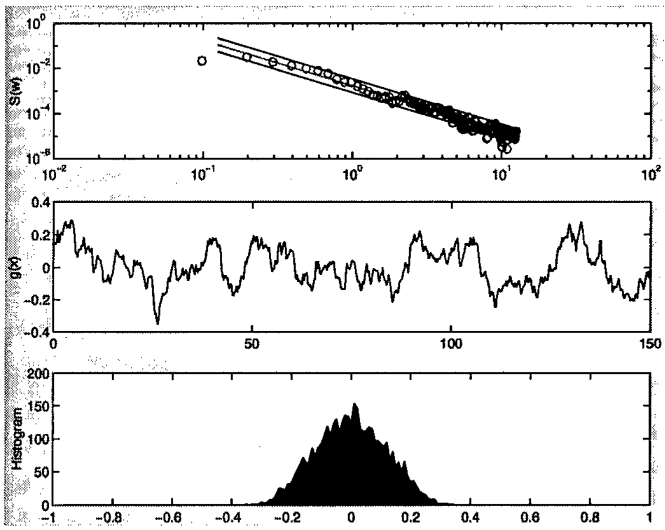
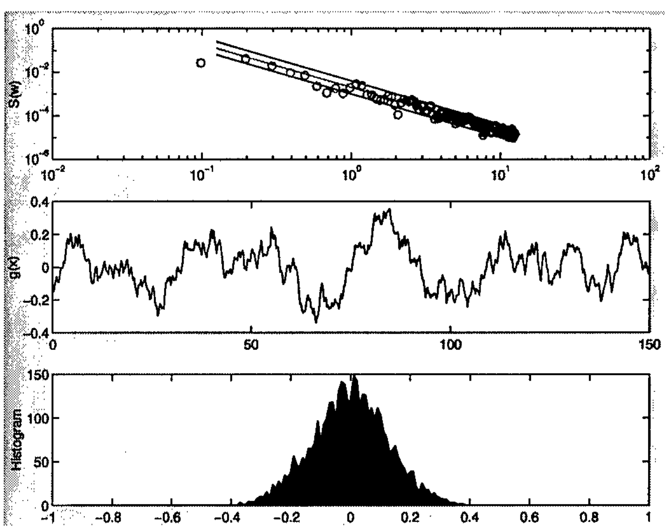


Figure 16 - 1.40" RMS



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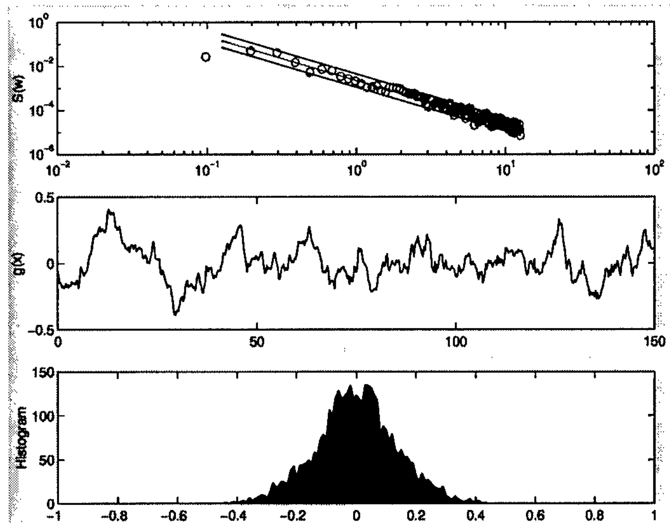

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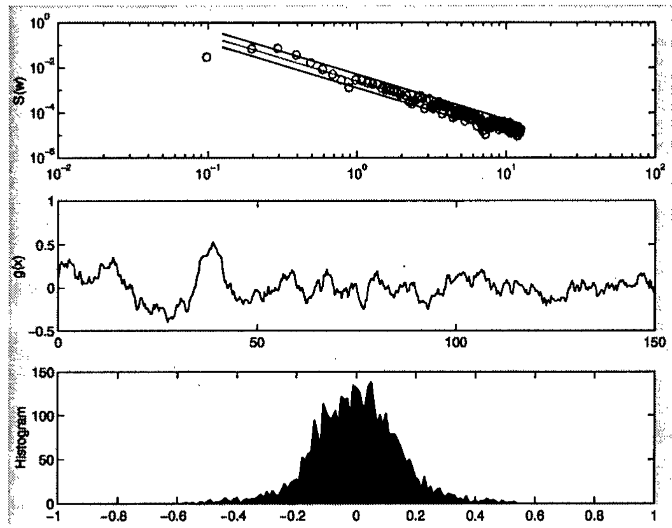

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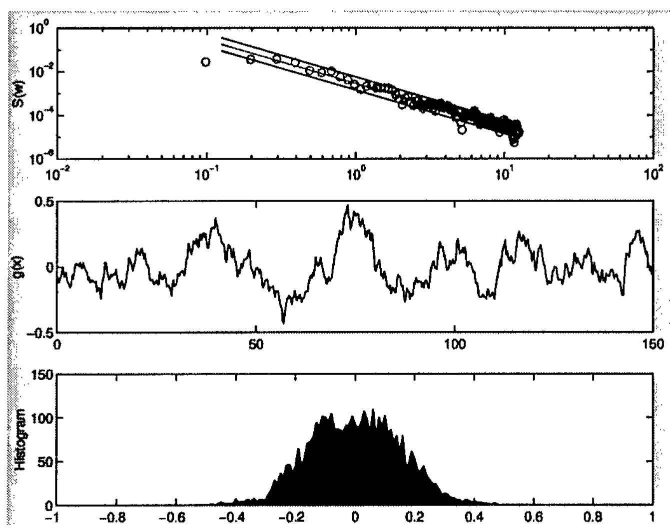

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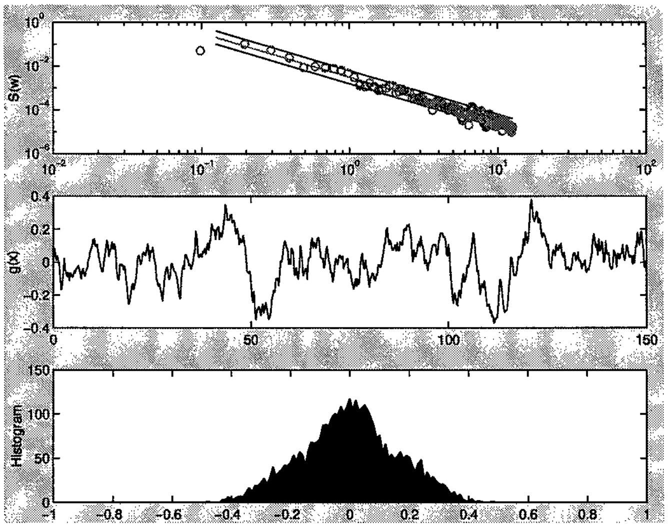

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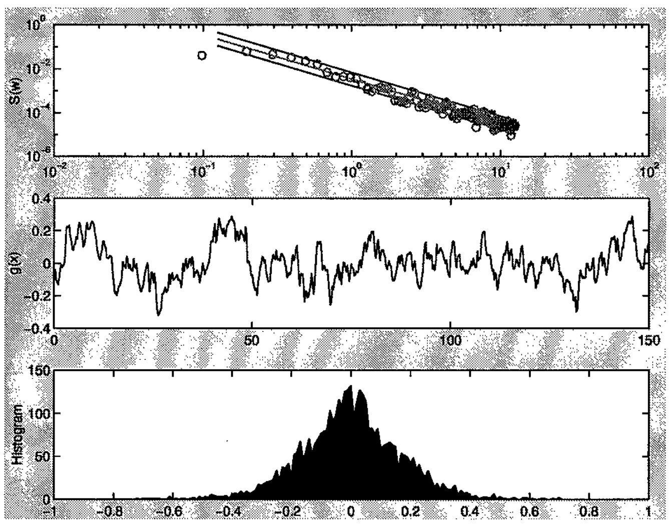

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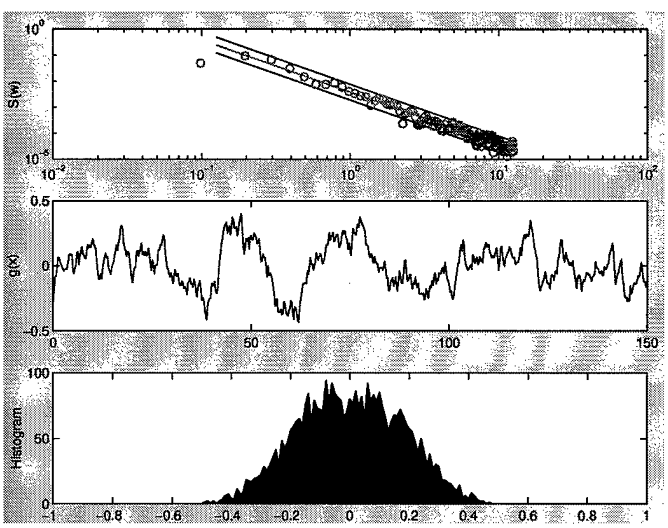

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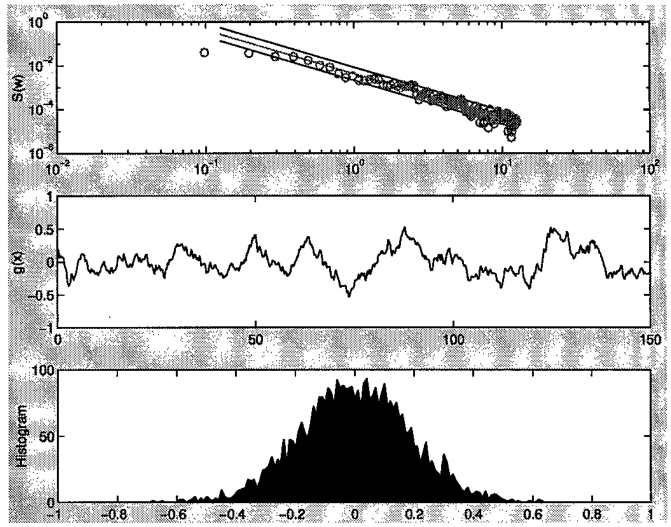

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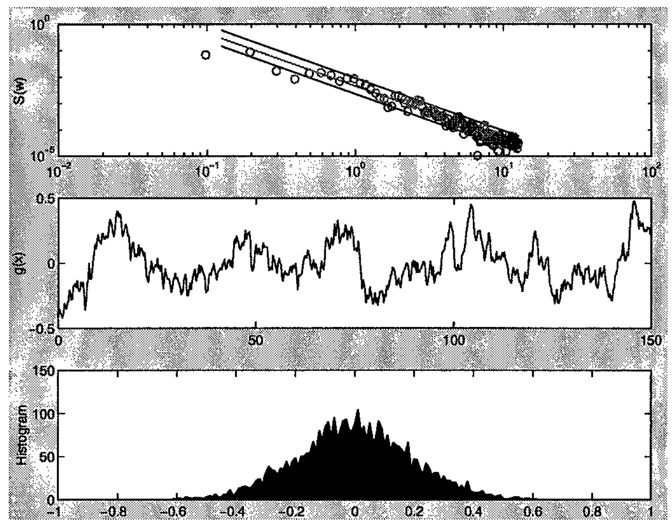

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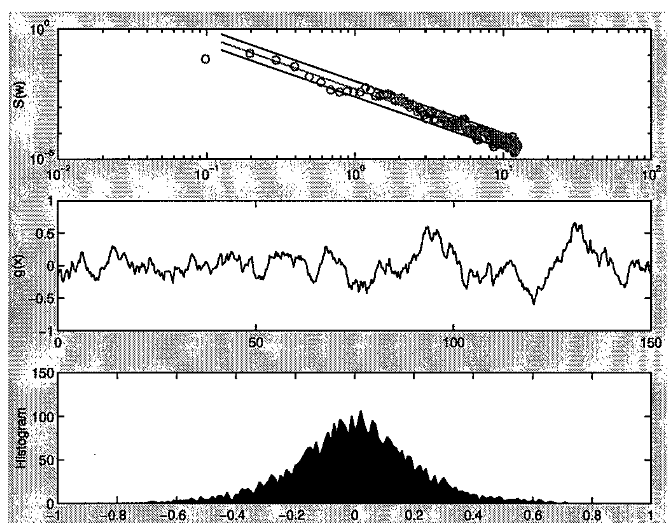

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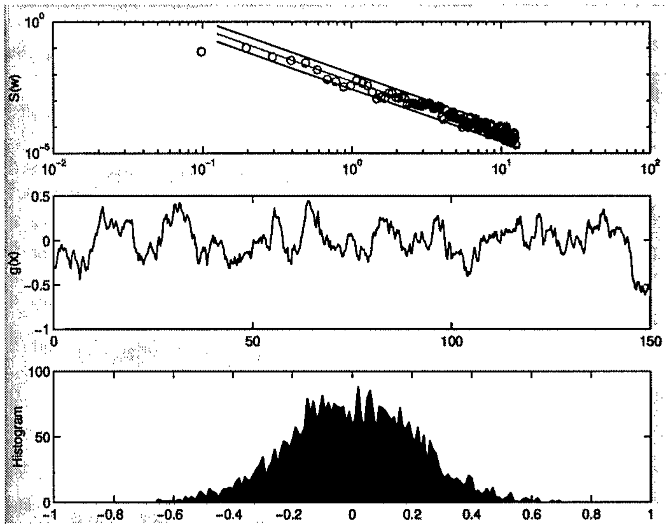

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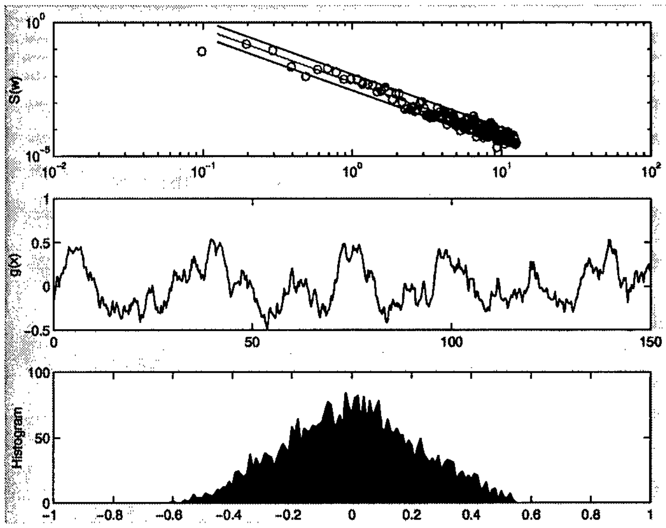

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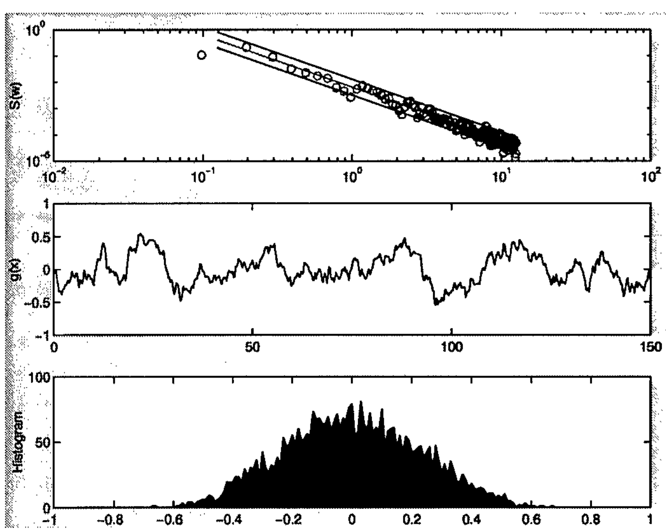

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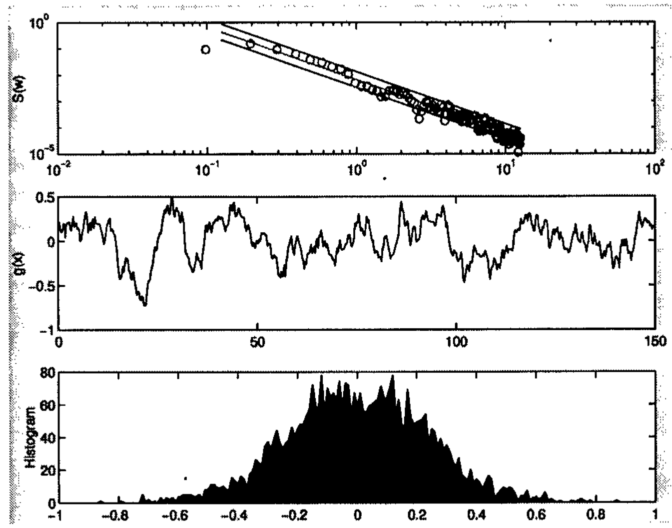

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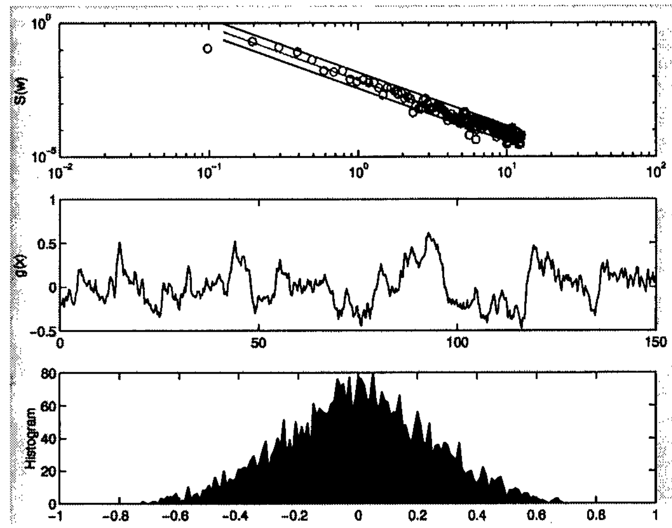

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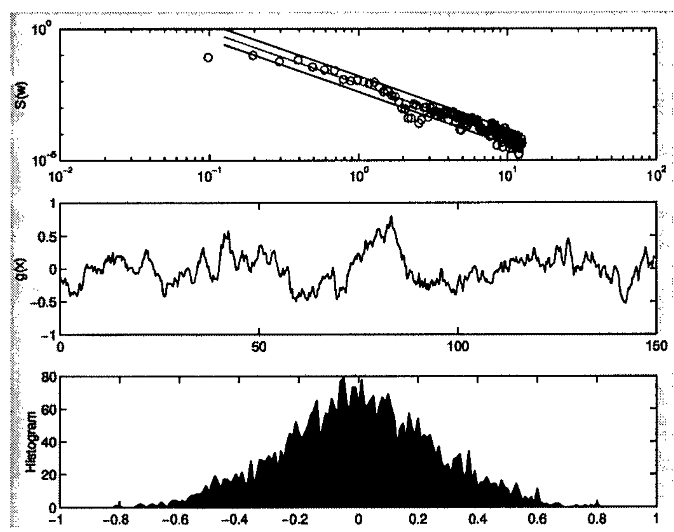

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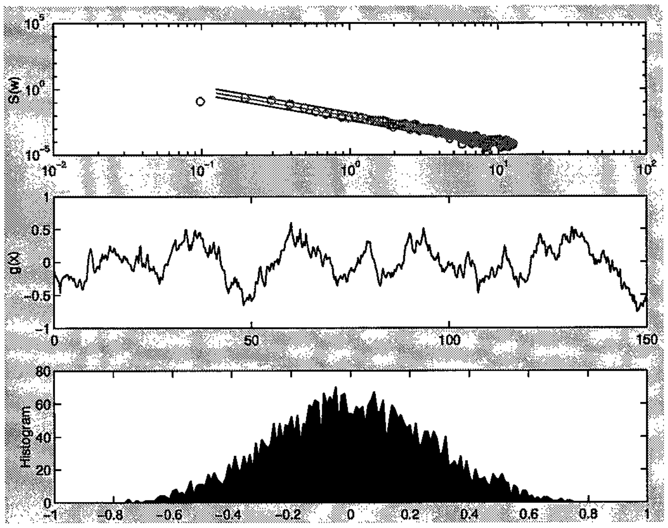

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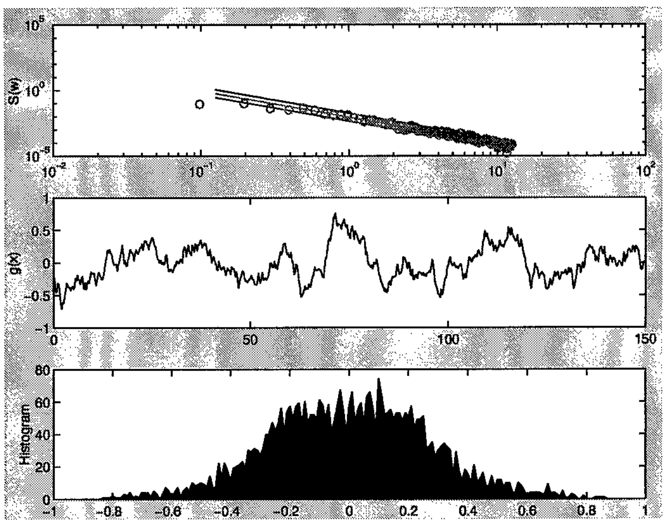

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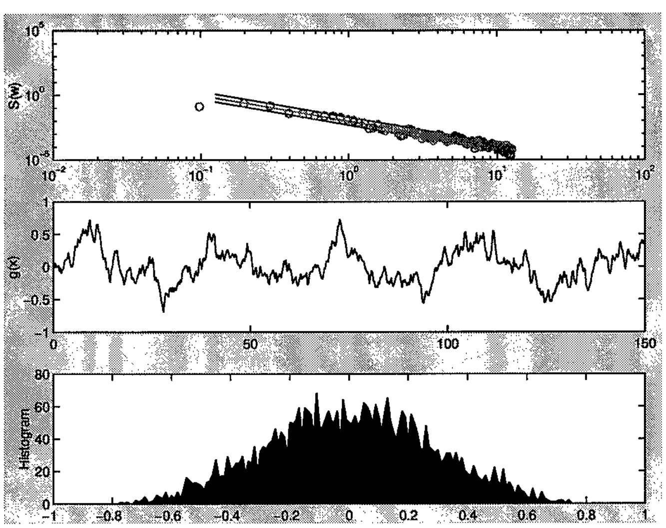

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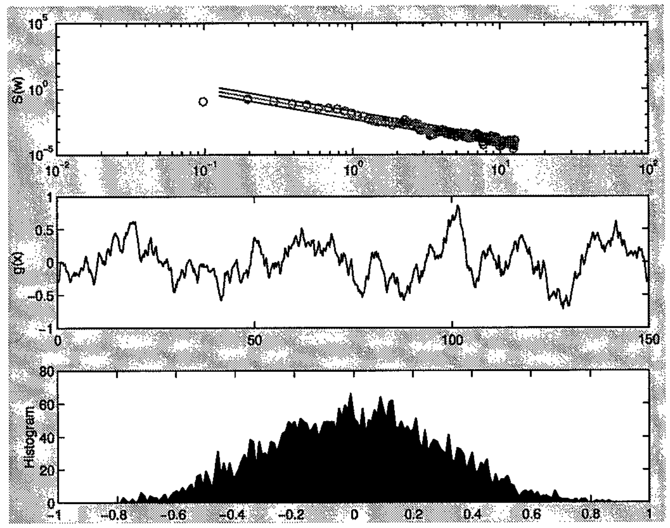

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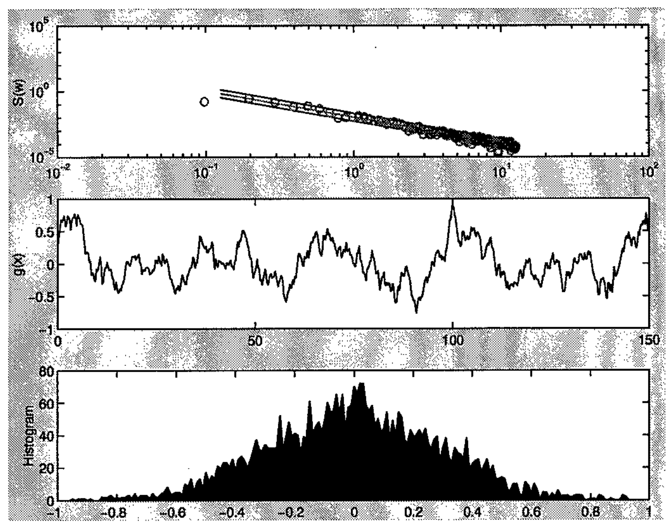

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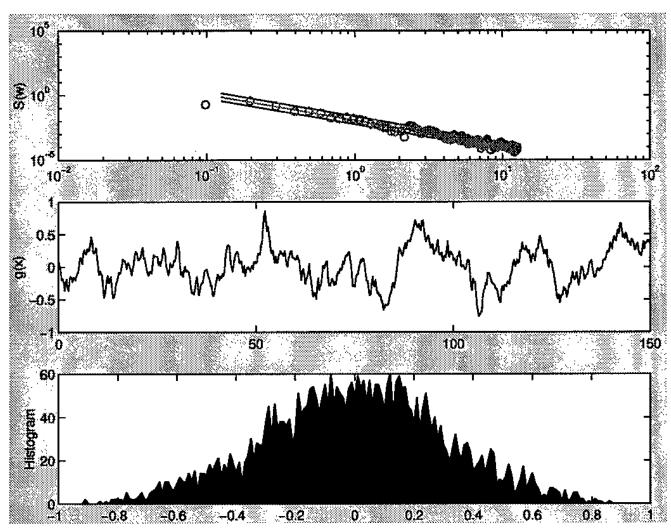

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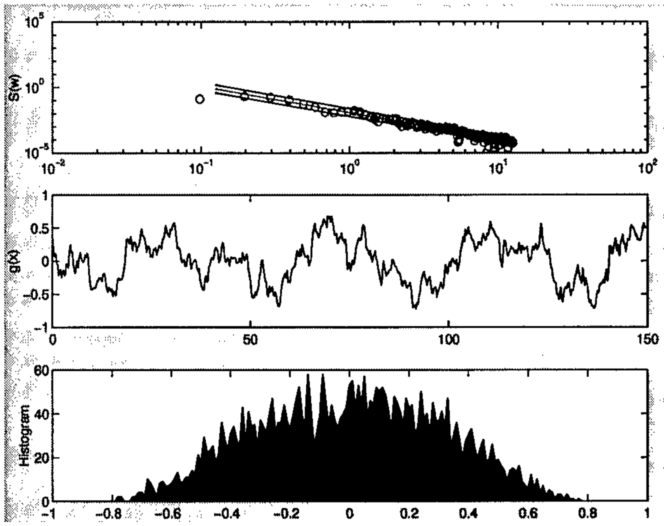

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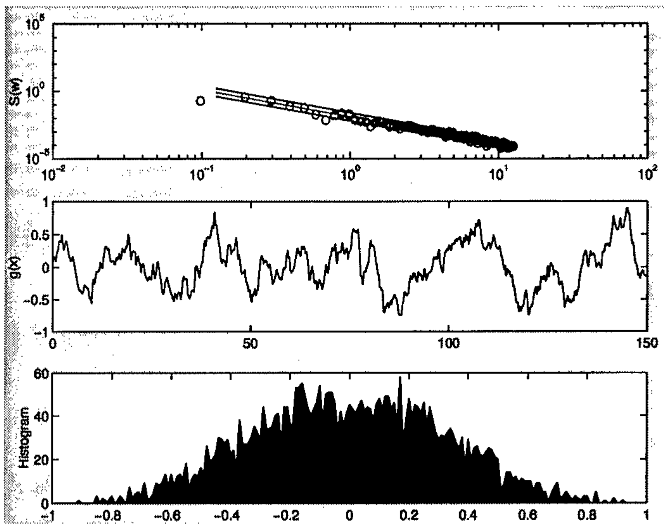

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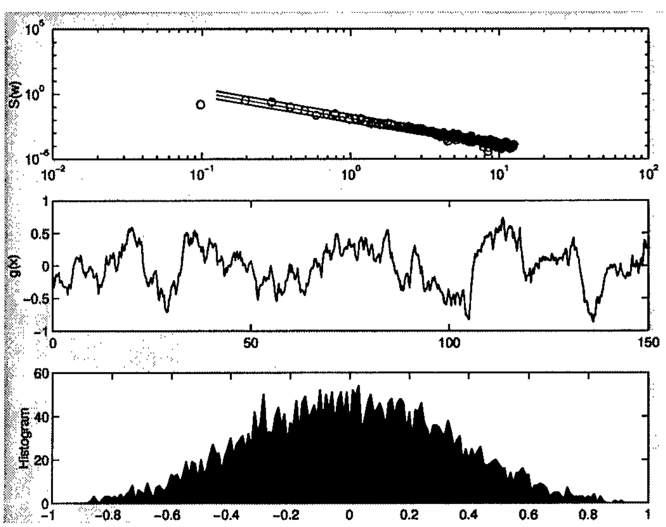

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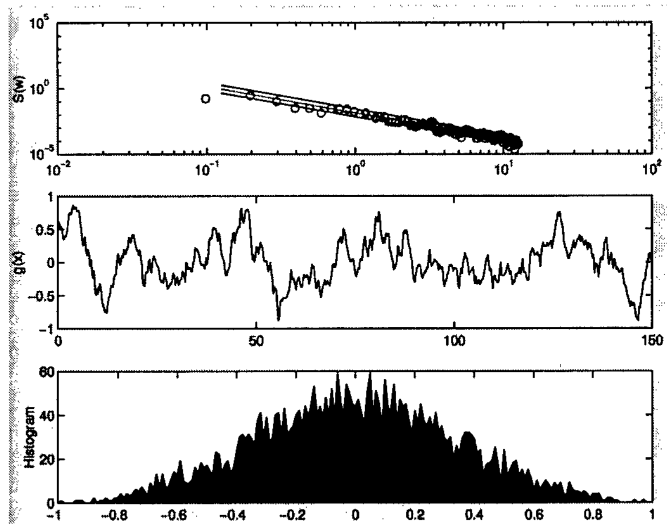

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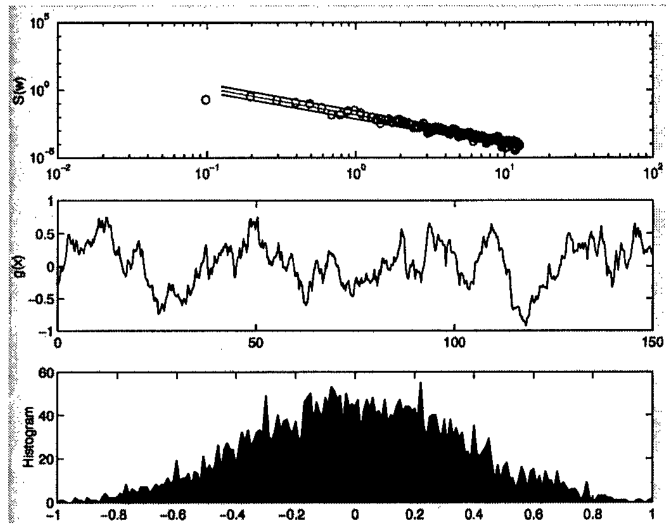

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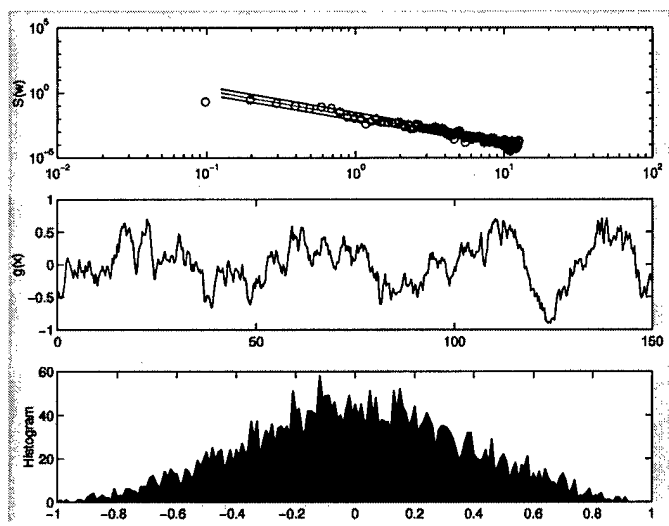

Figure 44 - 4.20" RMS

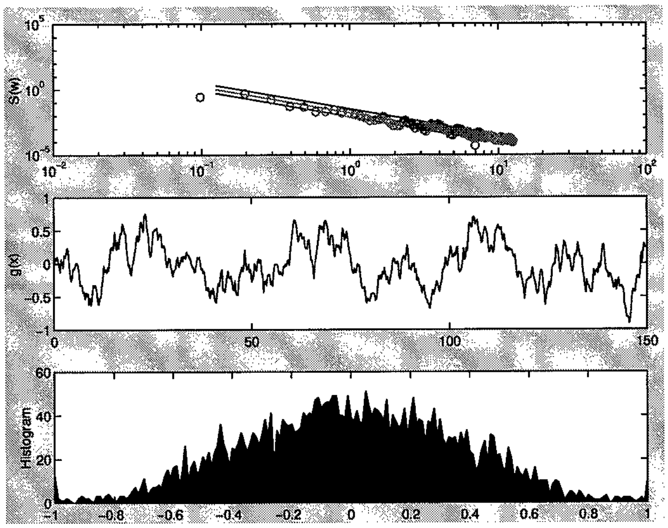

Figure 45 - 4.30" RMS

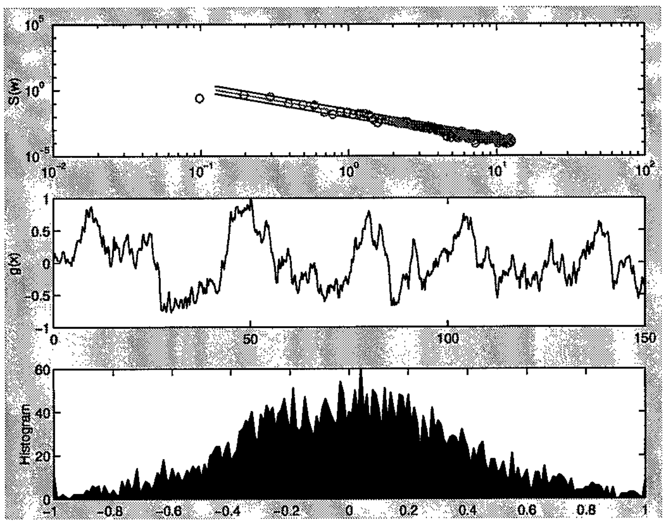

Figure 46 - 4.40" RMS

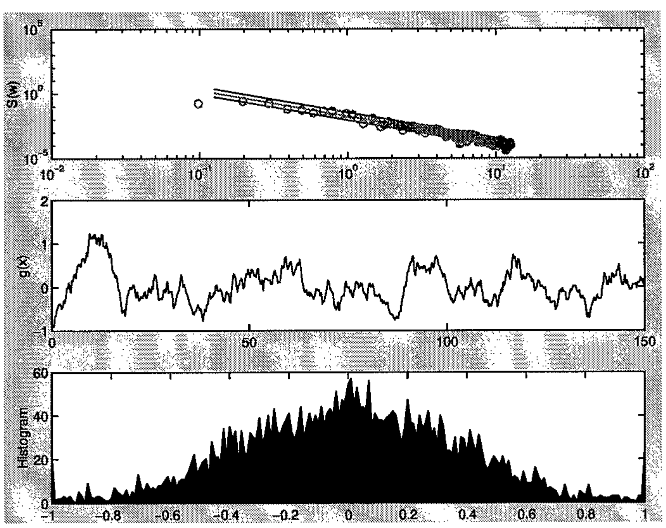

Figure 47 - 4.50" RMS

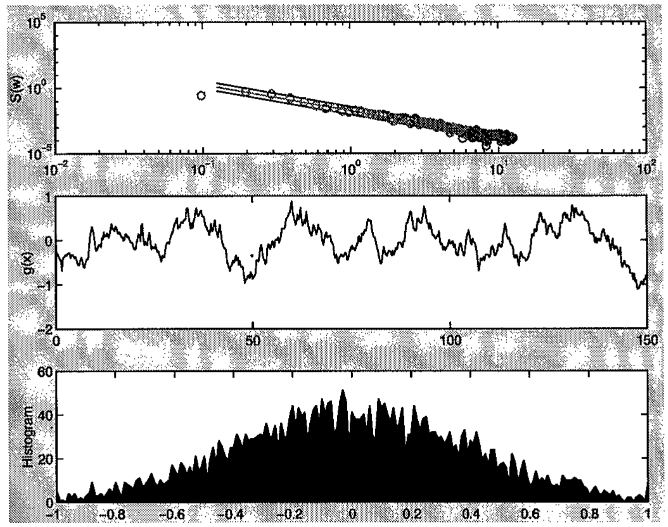

Figure 48 - 4.60" RMS

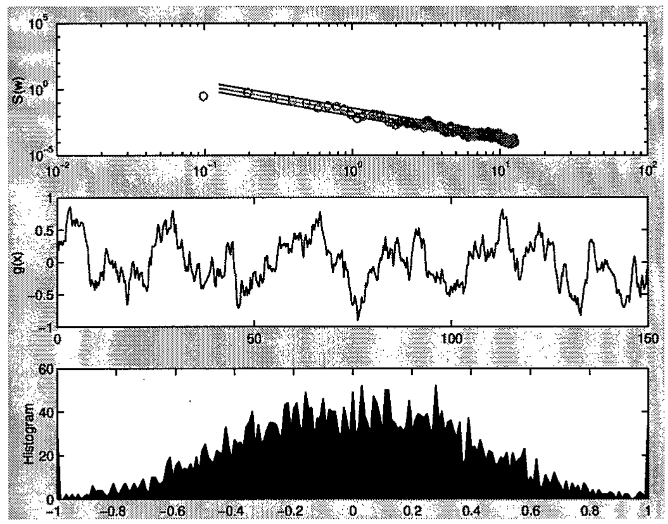

Figure 49 - 4.70" RMS

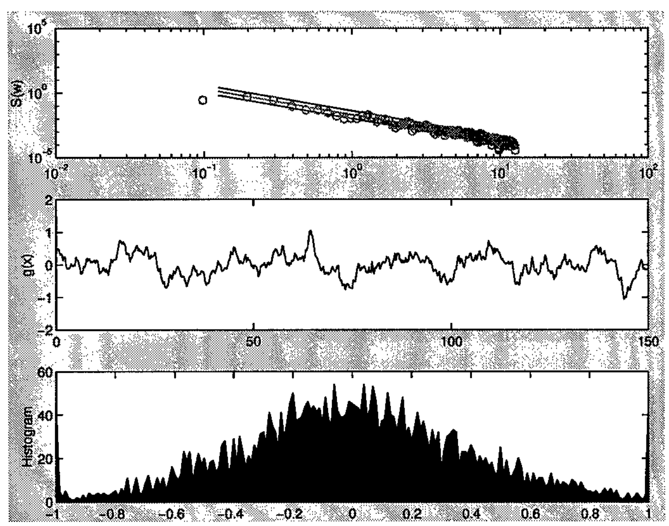

Figure 50 - 4.80" RMS

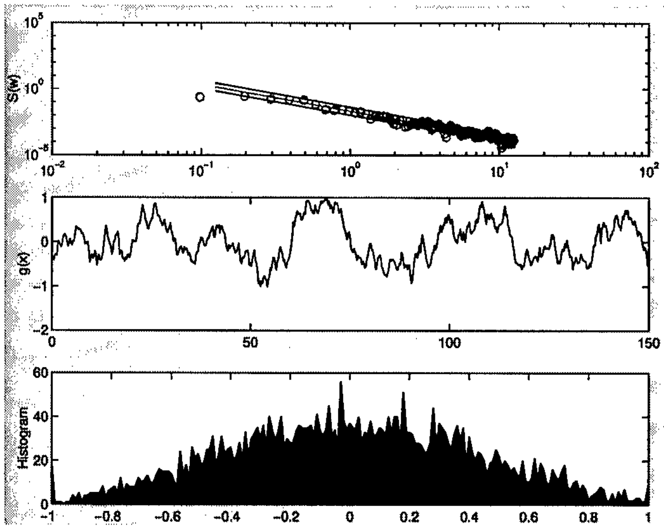

Figure 51 - 4.90" RMS

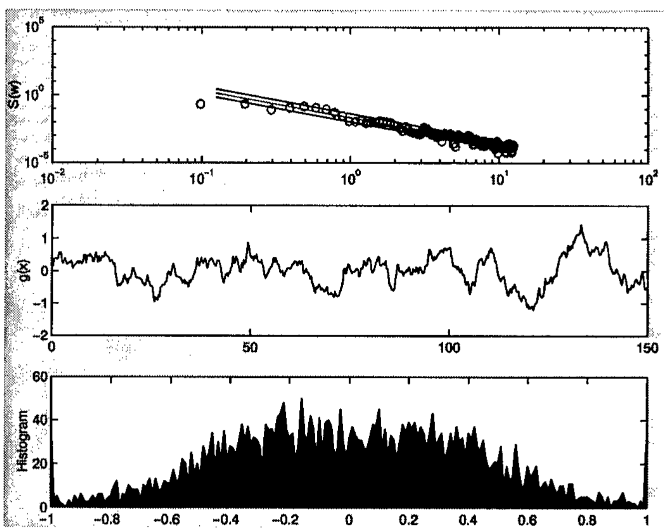

Figure 52 - 5.00" RMS

3.2 Full RMS Course Plots

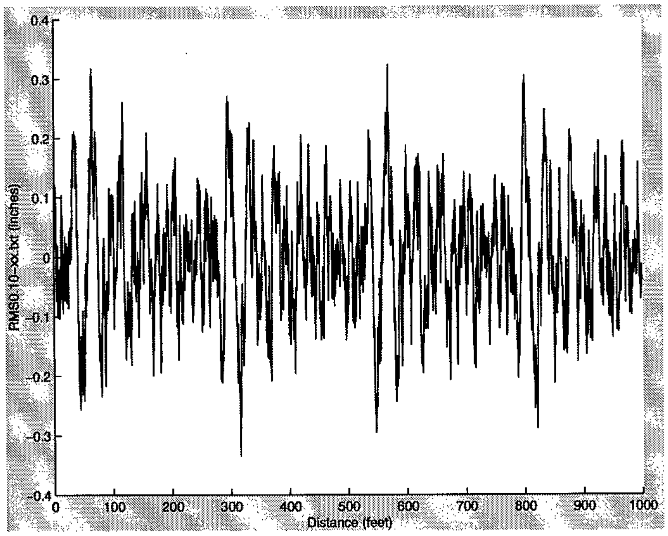

Figure 53 - 0.10" RMS

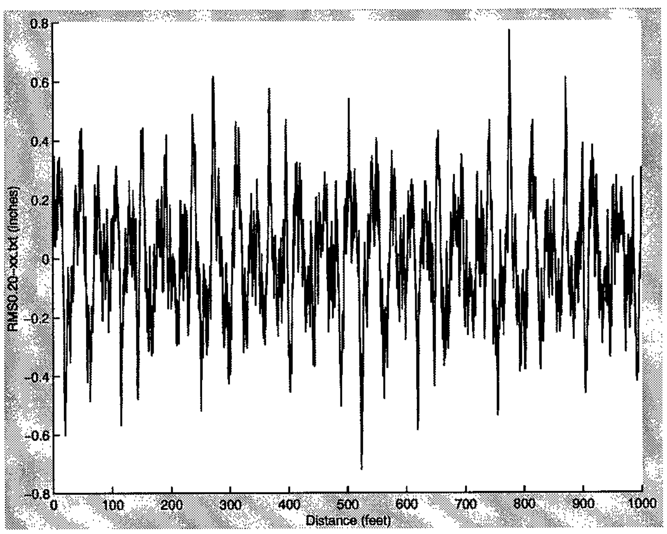

Figure 54 - 0.20" RMS

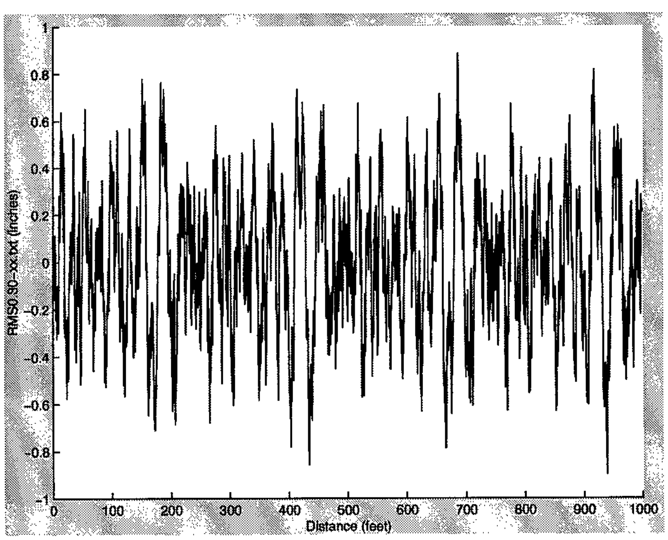

Figure 55 - 0.30" RMS

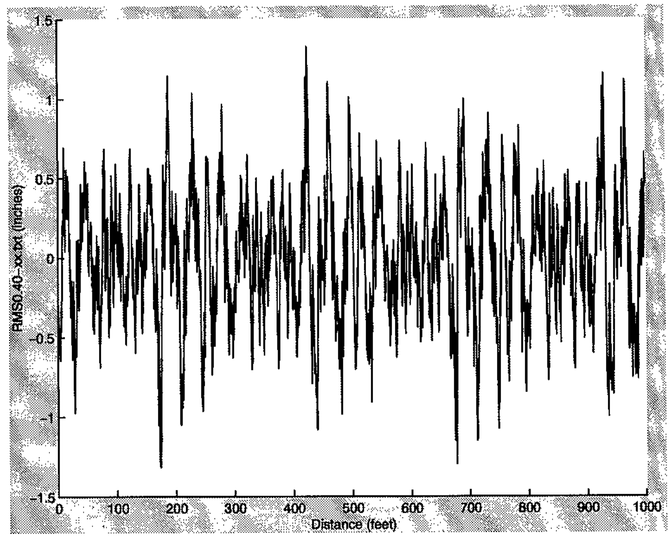

Figure 56 - 0.40" RMS

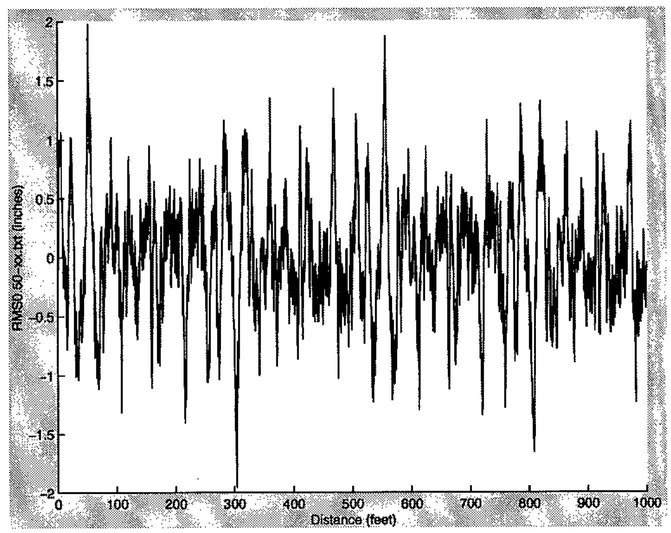

Figure 57 - 0.50" RMS

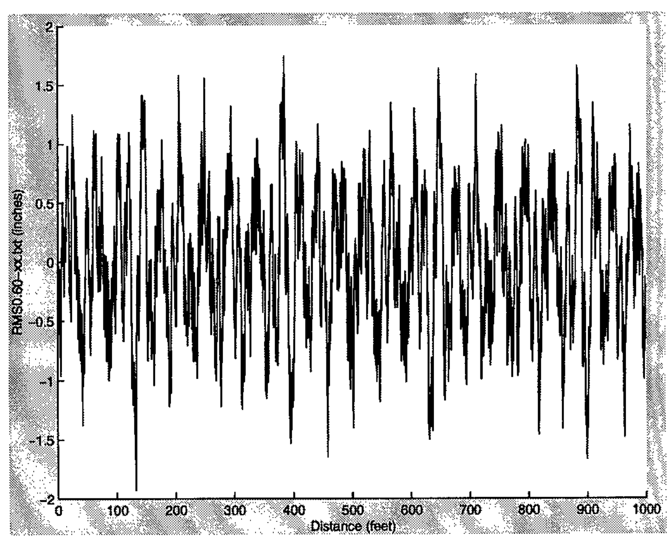

Figure 58 - 0.60" RMS

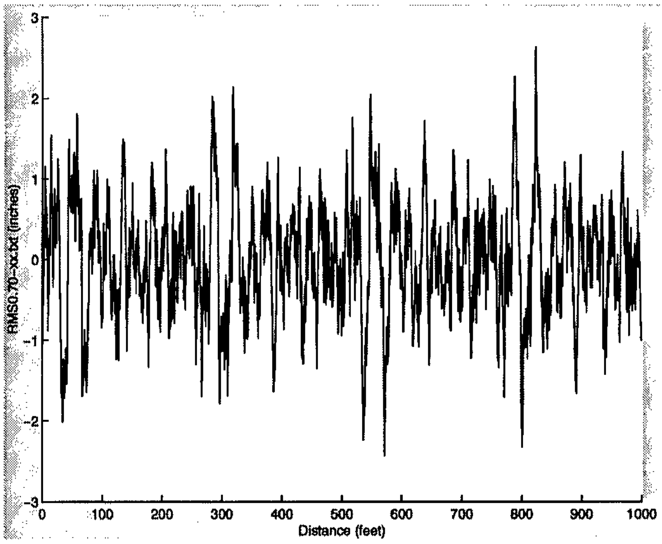

Figure 59 - 0.70" RMS

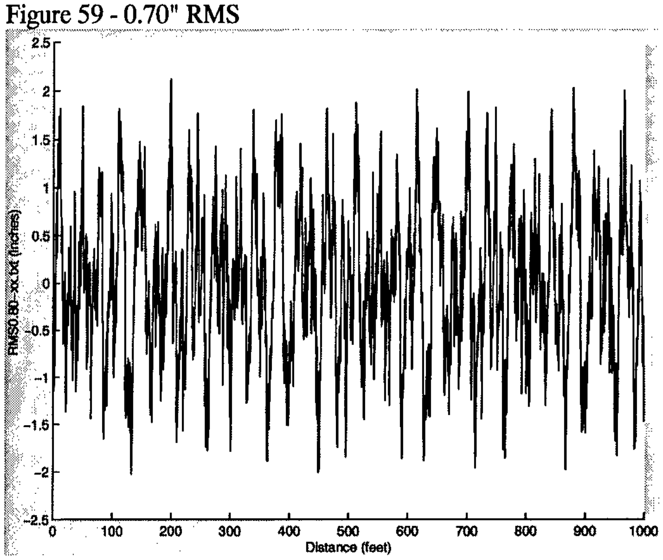

Figure 60 - 0.80" RMS

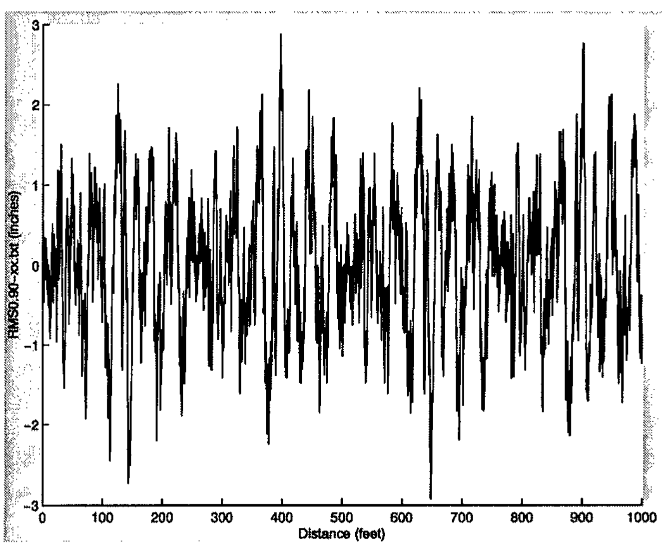

Figure 61 - 0.90" RMS

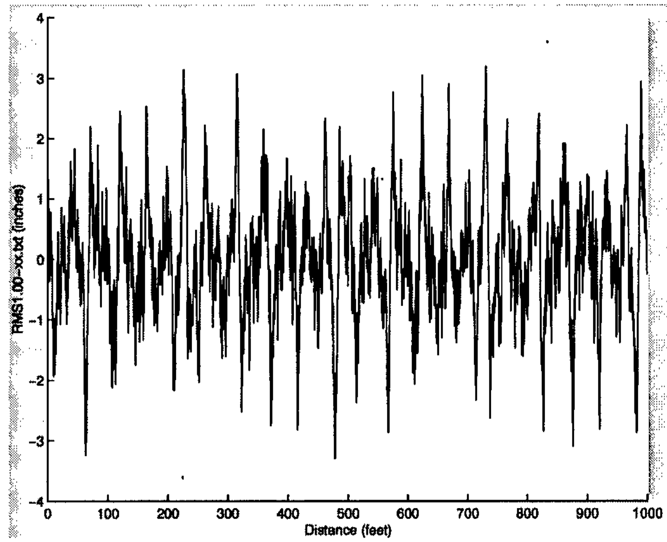

Figure 62 - 1.00" RMS

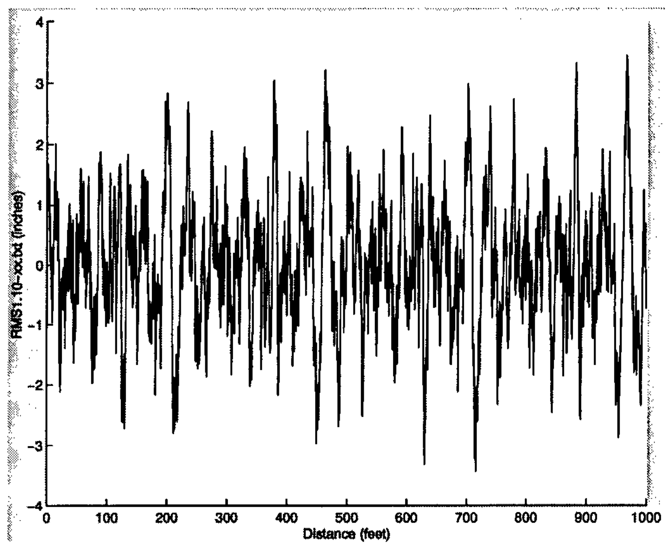

Figure 63 - 1.10" RMS

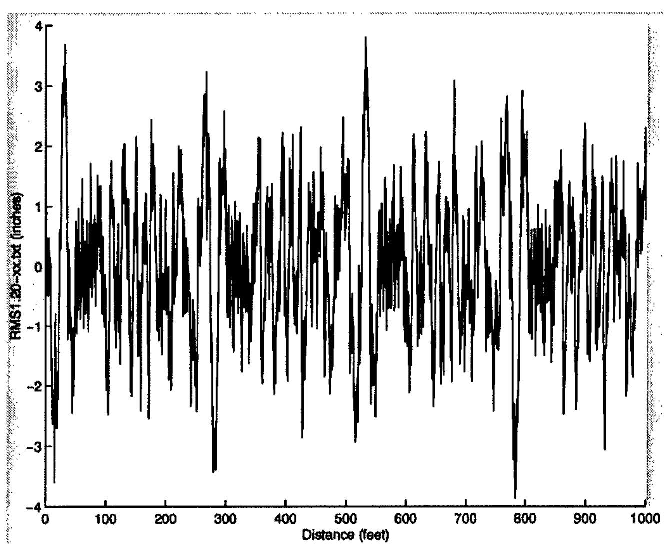

Figure 64 - 1.20" RMS

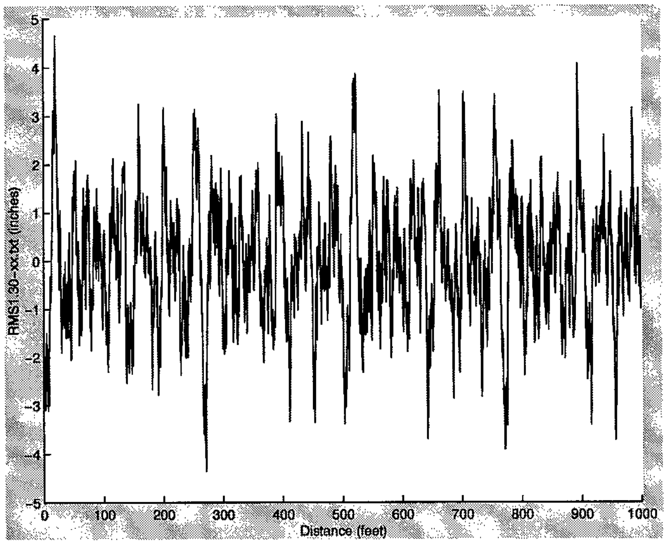

Figure 65 - 1.30" RMS

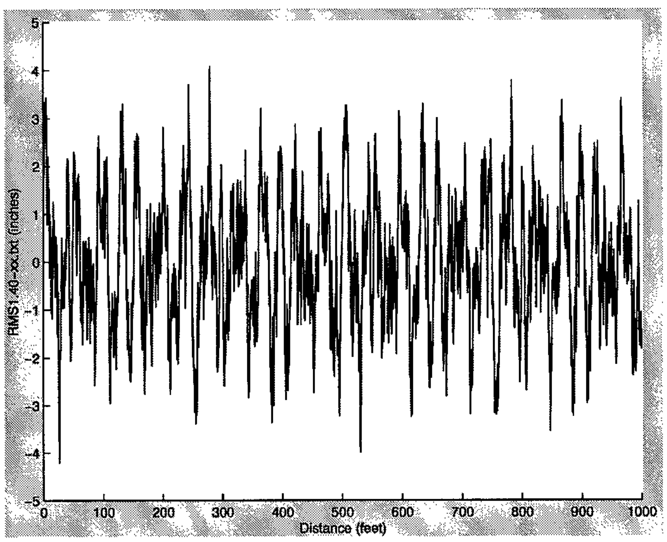

Figure 66 - 1.40" RMS

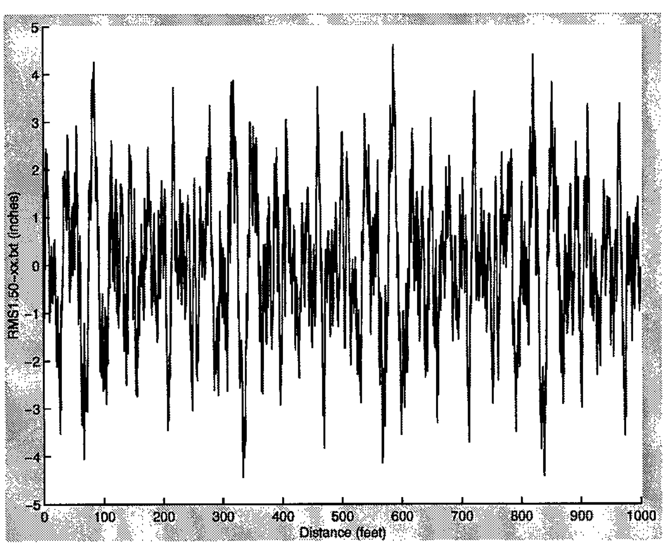

Figure 67 - 1.50" RMS

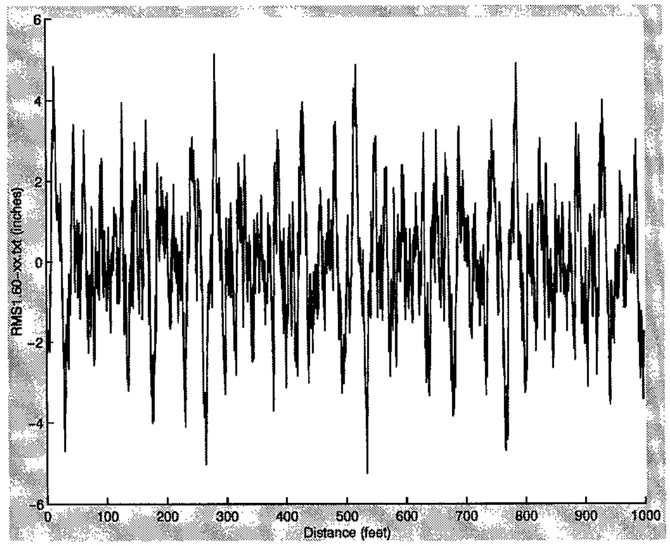

Figure 68 - 1.60" RMS

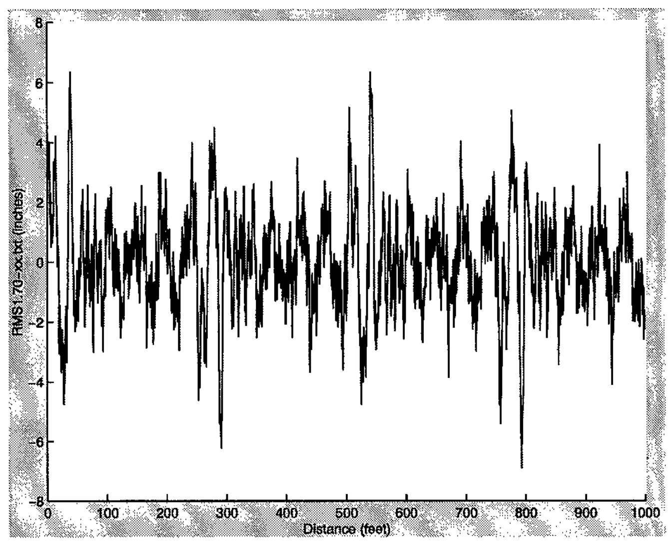

Figure 69 - 1.70" RMS

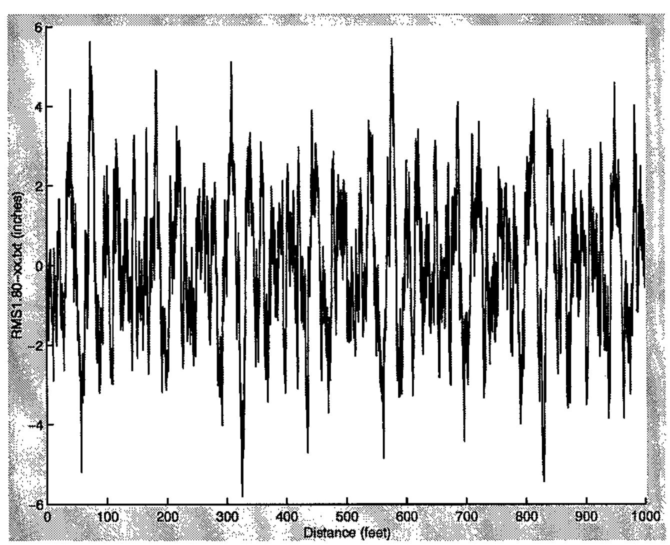

Figure 70 - 1.80" RMS

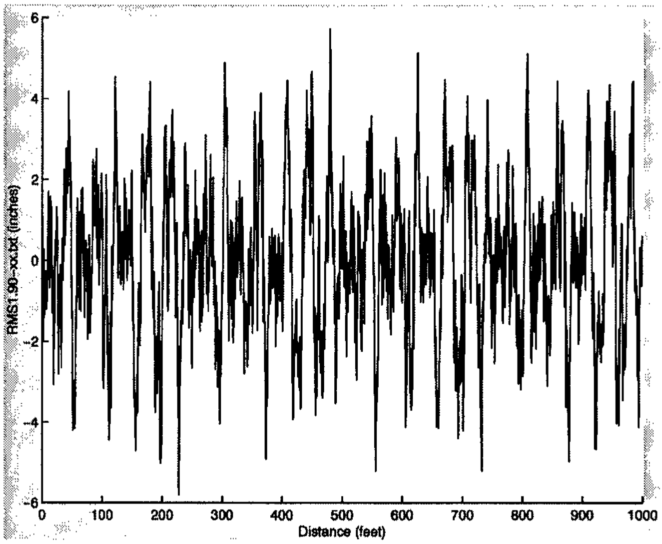

Figure 71 - 1.90" RMS

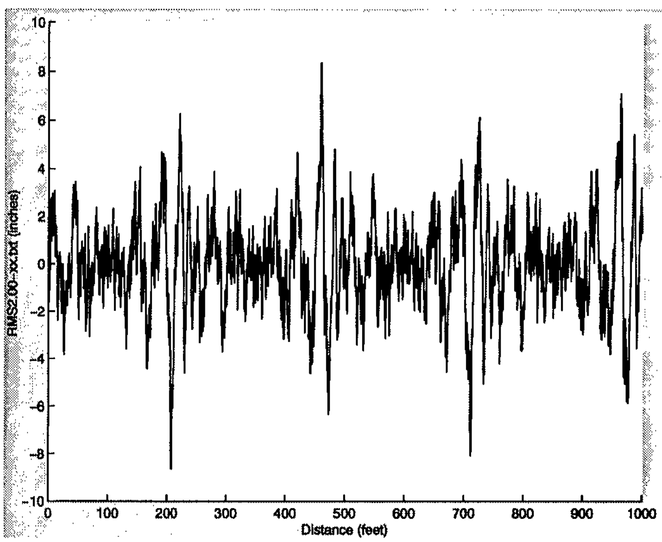

Figure 72 - 2.00" RMS

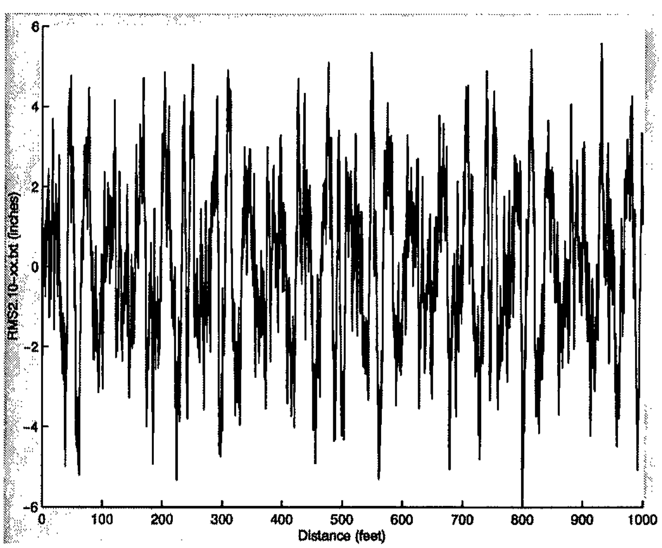

Figure 73 - 2.10" RMS

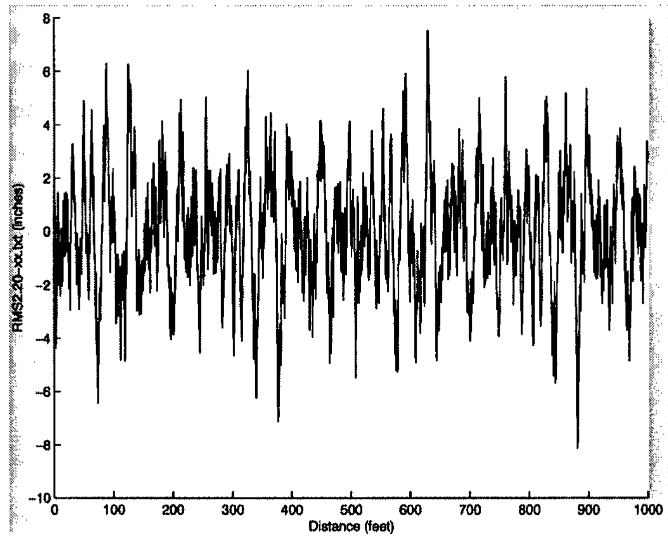

Figure 74 - 2.20" RMS

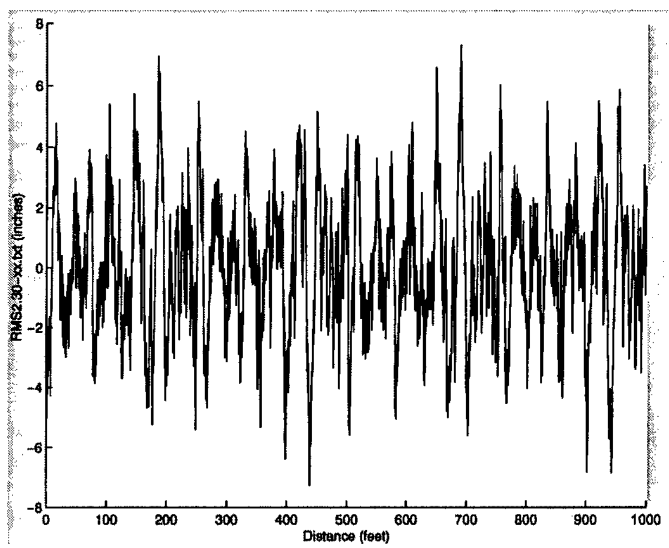

Figure 75 - 2.30" RMS

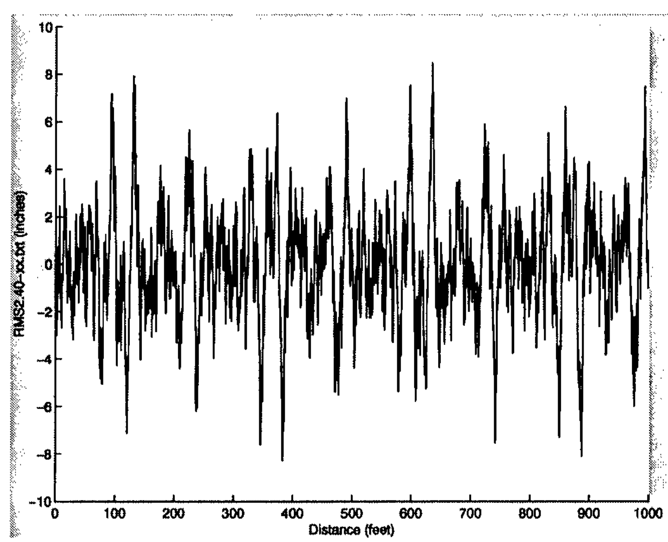

Figure 76 - 2.40" RMS

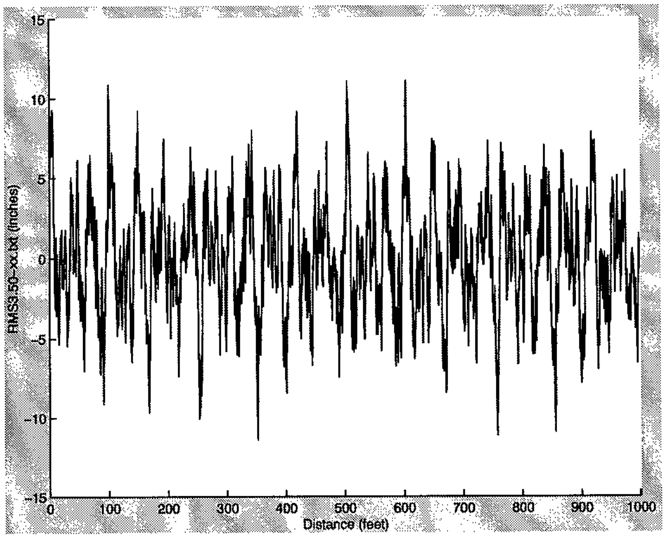

Figure 77 - 2.50" RMS

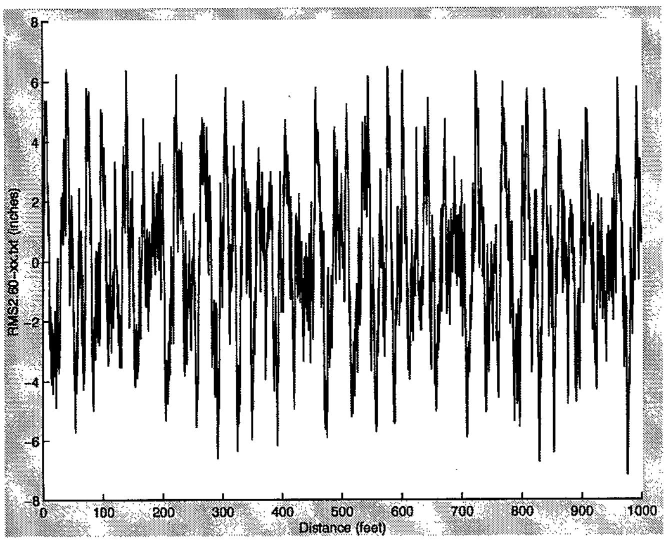

Figure 78 - 2.60" RMS

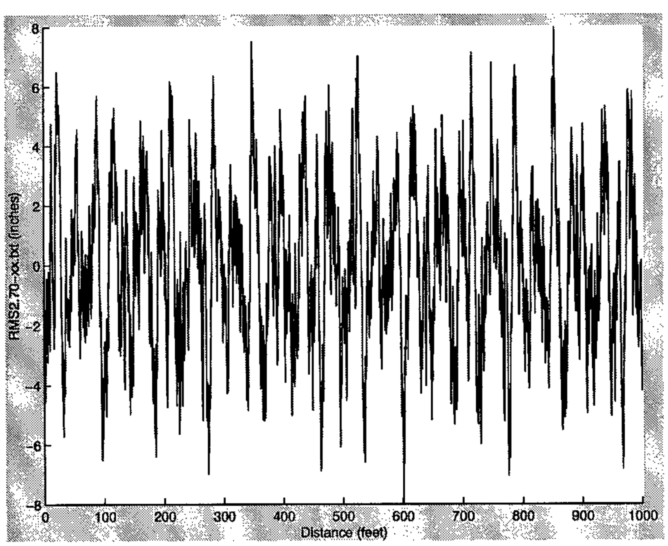

Figure 79 - 2.70" RMS

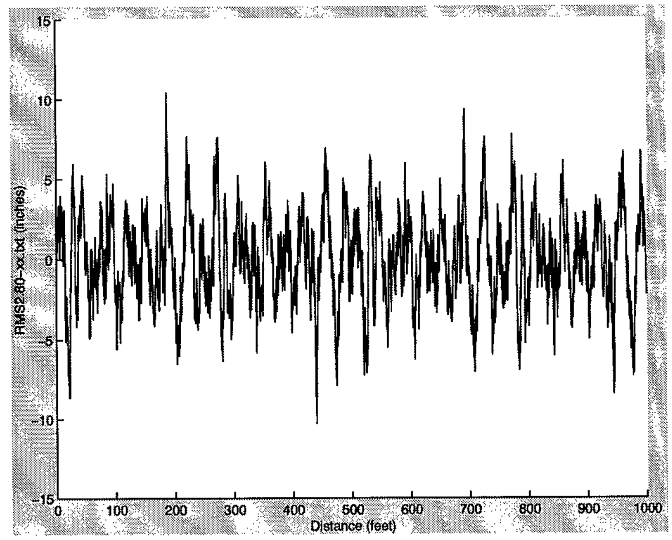

Figure 80 - 2.80" RMS

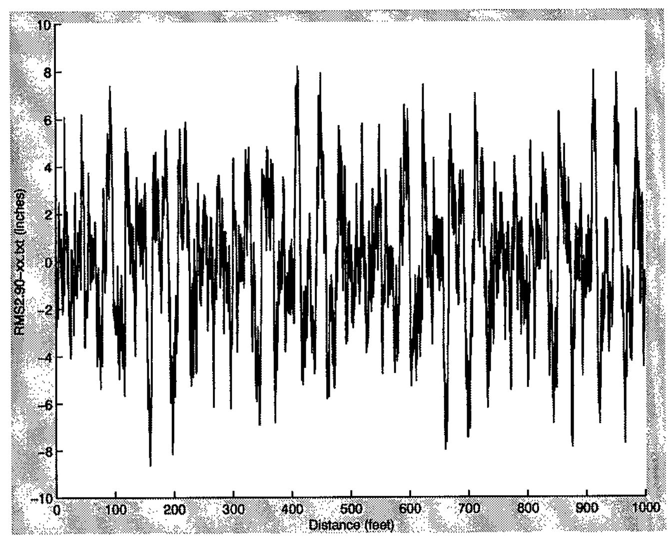

Figure 81 - 2.90" RMS

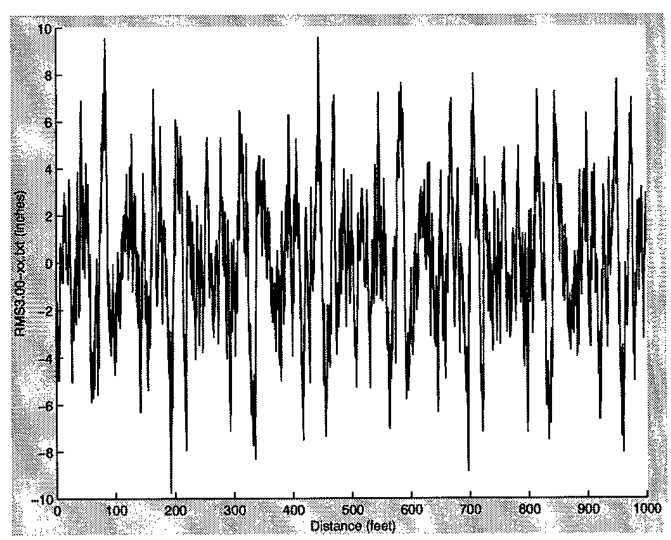

Figure 82 - 3.00" RMS

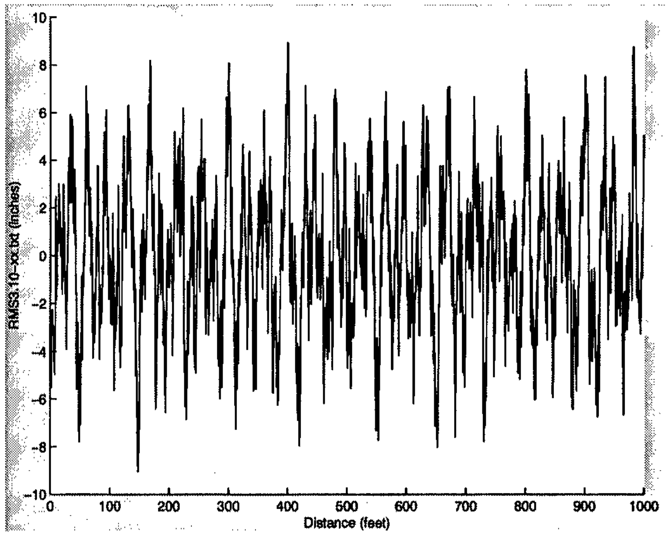

Figure 83 - 3.10" RMS

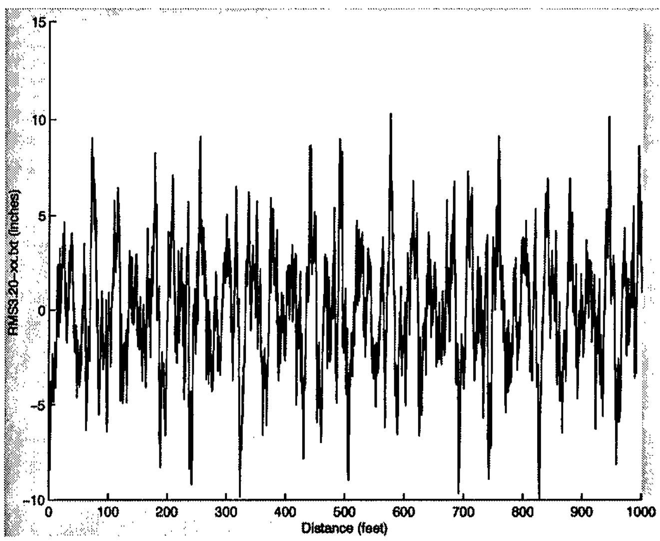

Figure 84 - 3.20" RMS

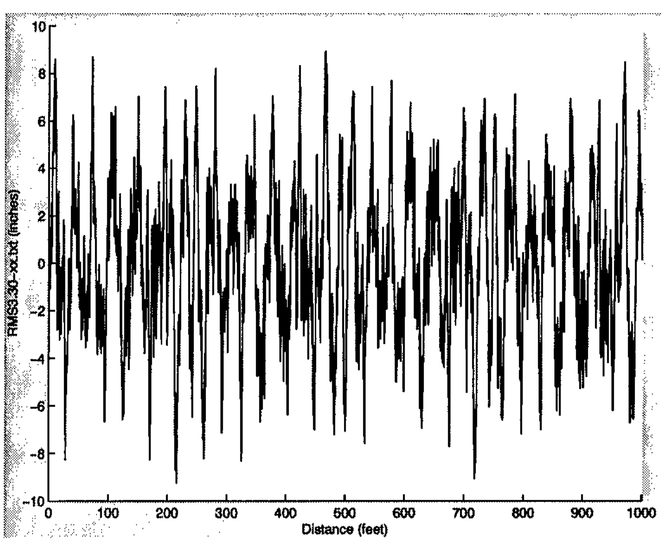

Figure 85 - 3.30" RMS

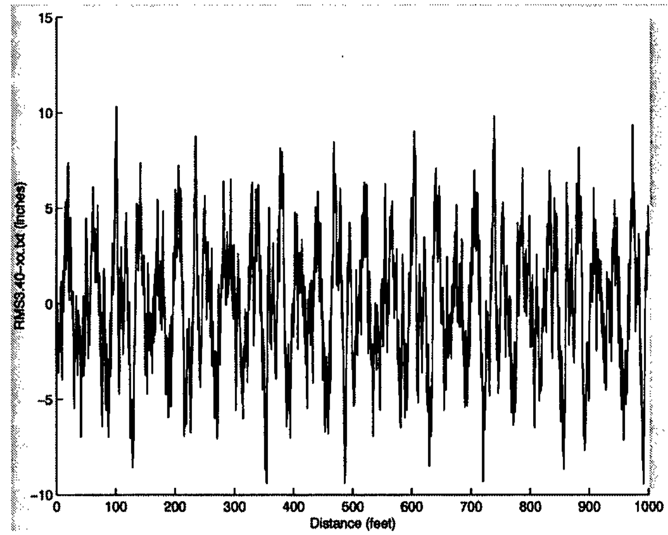

Figure 86 - 3.40" RMS

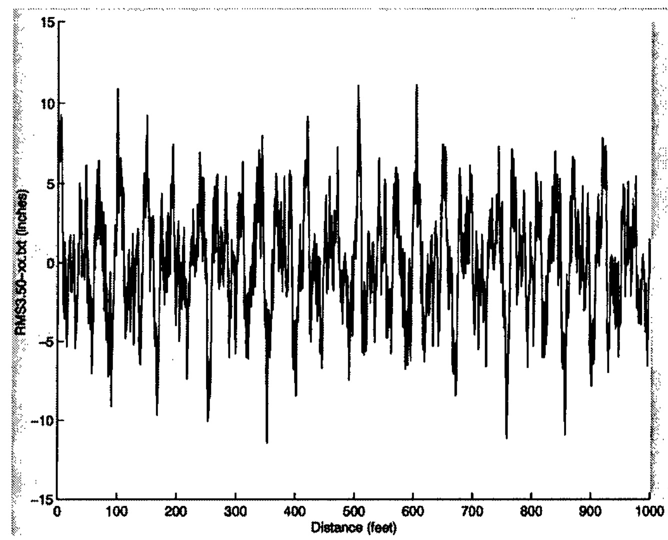

Figure 87 - 3.50" RMS

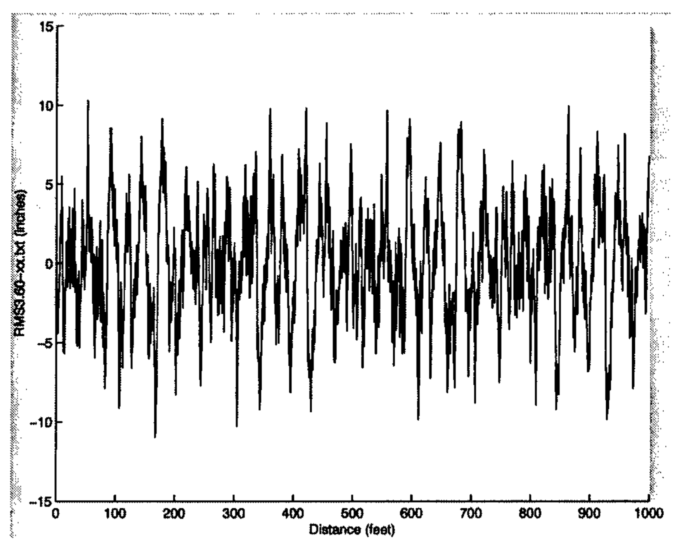

Figure 88 - 3.60" RMS

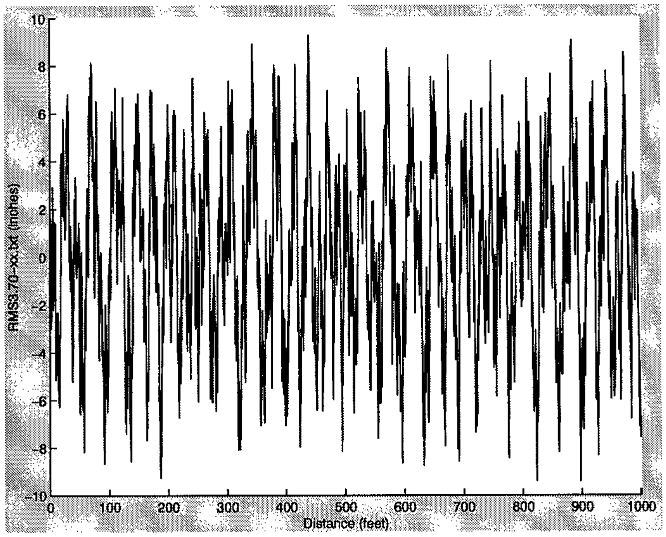

Figure 89 - 3.70" RMS

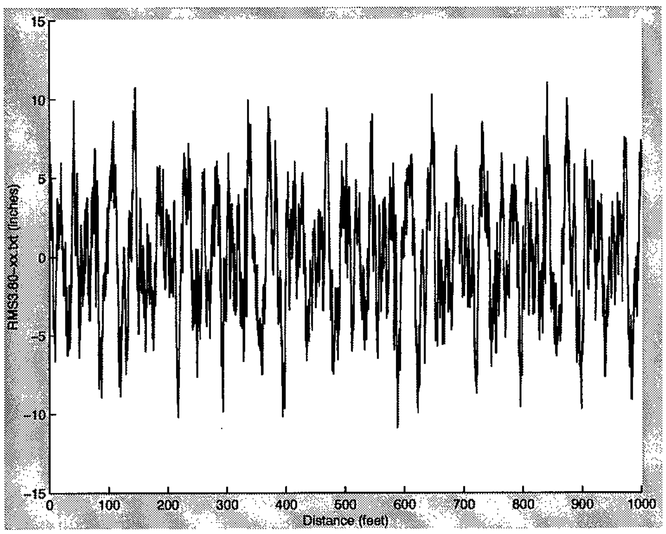

Figure 90 - 3.80" RMS

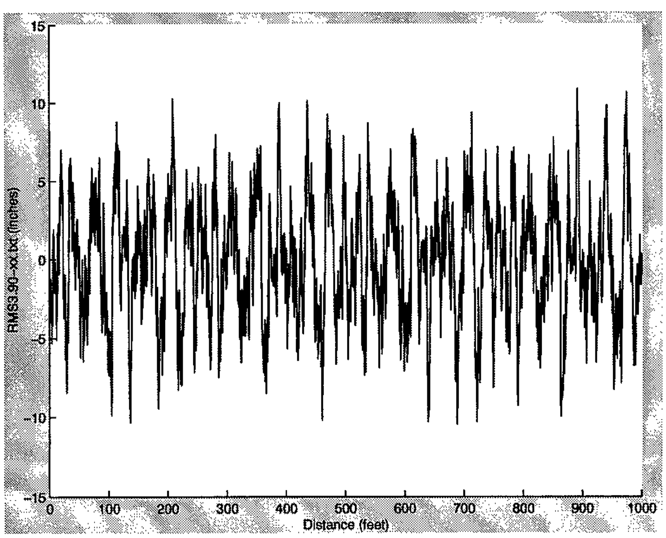

Figure 91 - 3.90" RMS

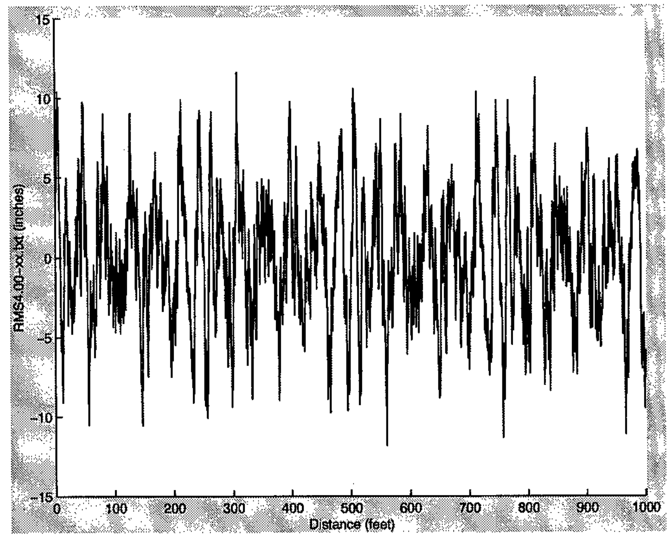

Figure 92 - 4.00" RMS

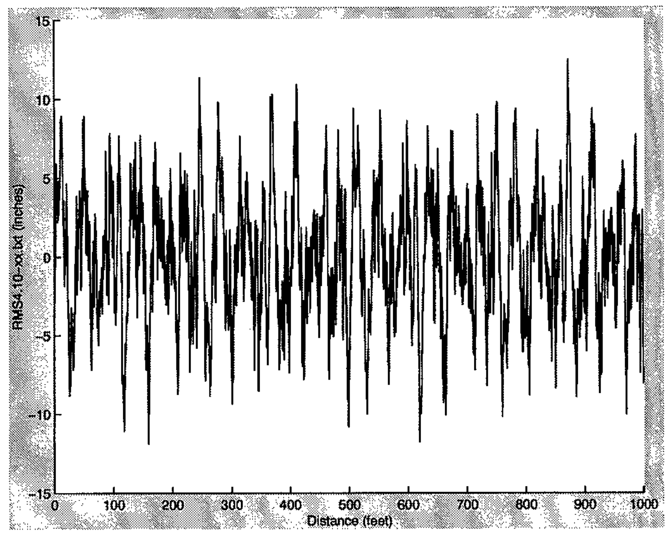

Figure 93 - 4.10" RMS

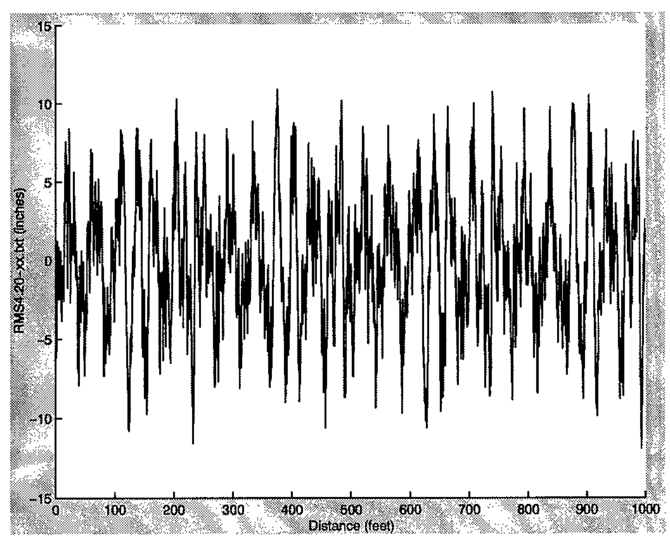

Figure 94 - 4.20" RMS

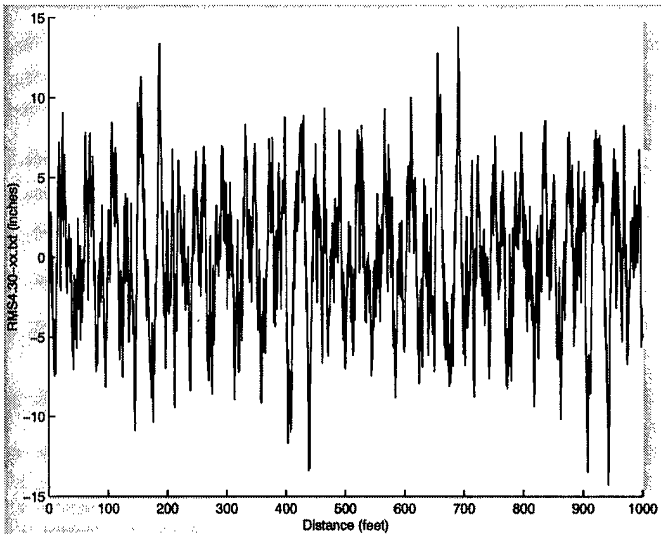

Figure 95 - 4.30" RMS

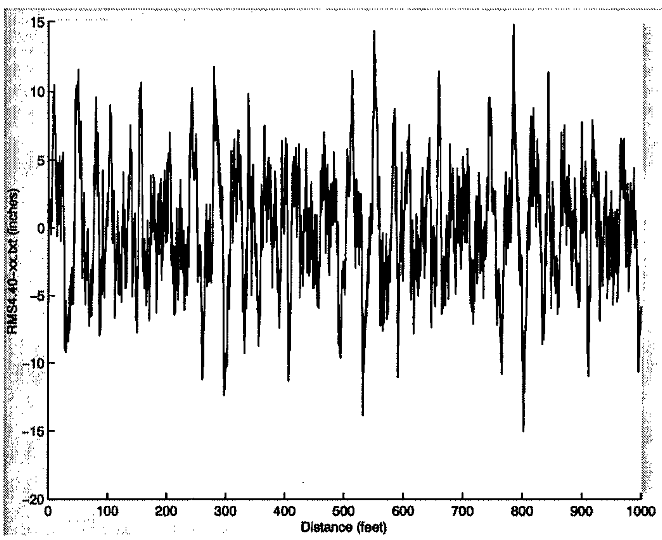

Figure 96 - 4.40" RMS

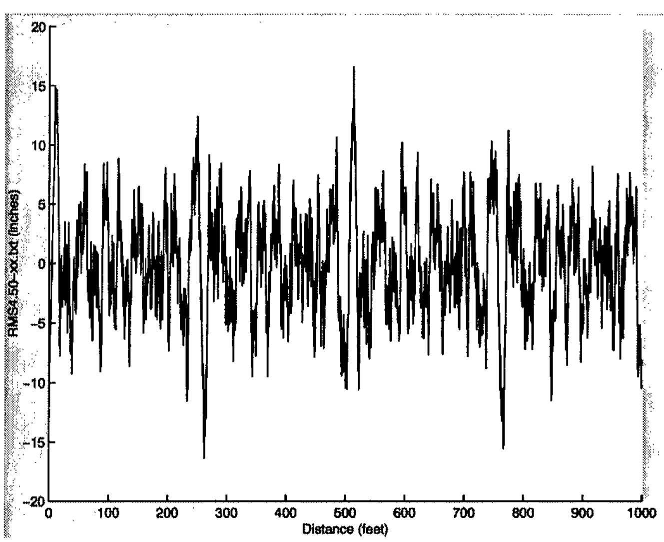

Figure 97 - 4.50" RMS

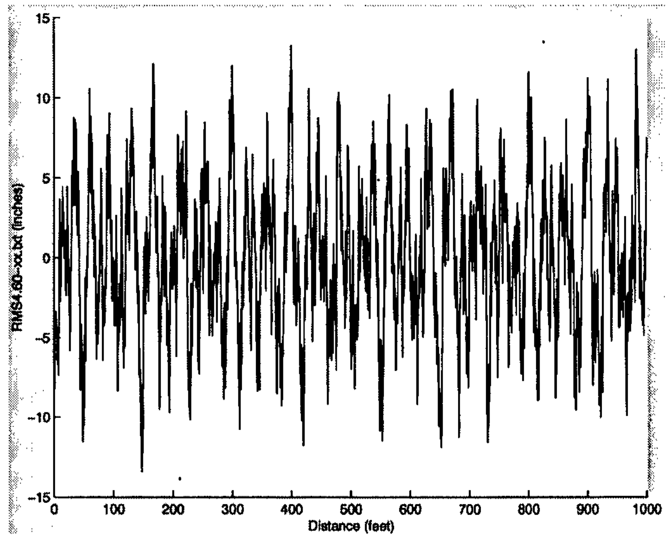

Figure 98 - 4.60" RMS

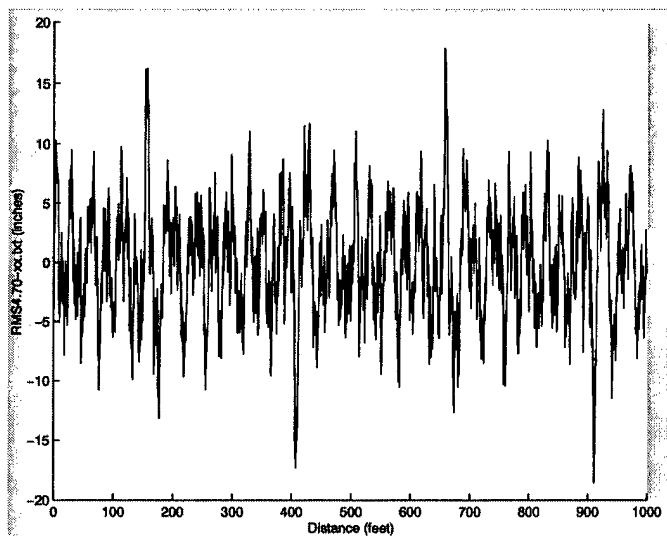

Figure 99 - 4.70" RMS

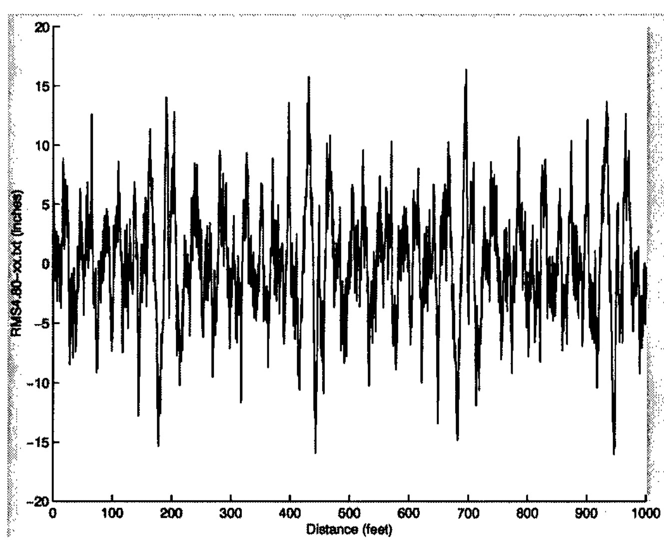

Figure 100 - 4.80" RMS

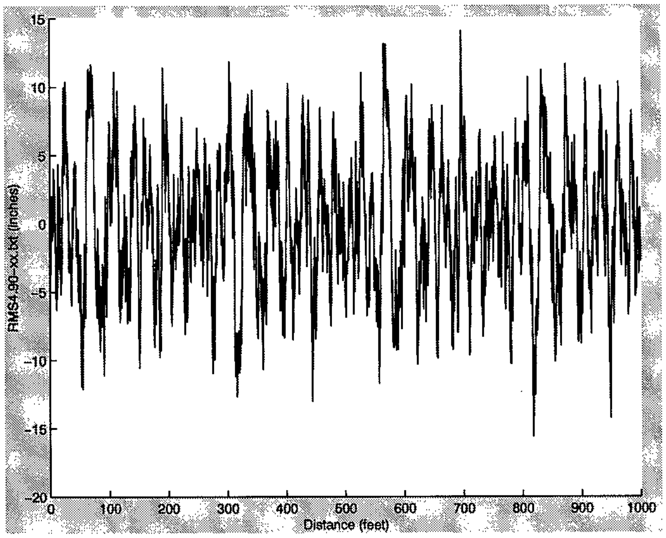

Figure 101 - 4.90" RMS

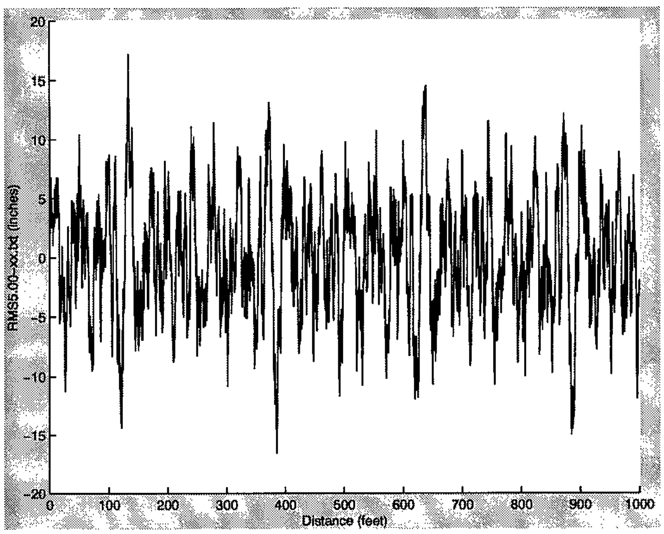

Figure 102 - 5.00" RMS

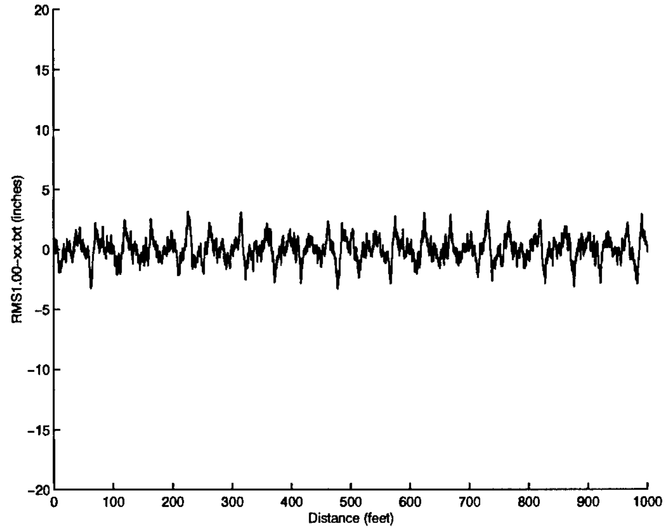

Figure 103 - Scaled 1.00" RMS

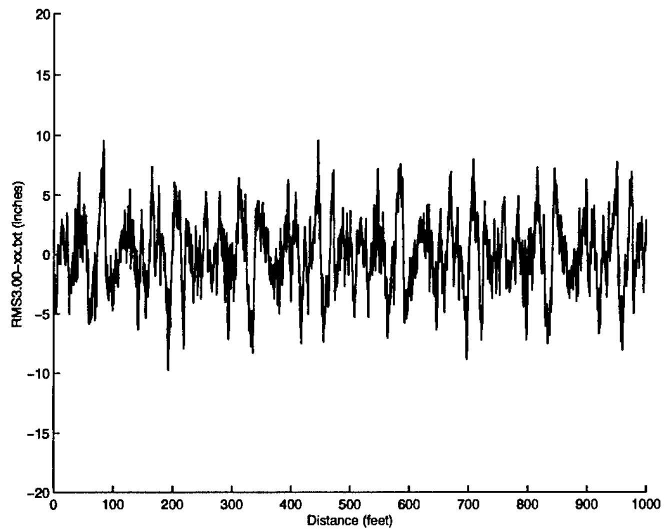

Figure 104 - Scaled 3.00" RMS

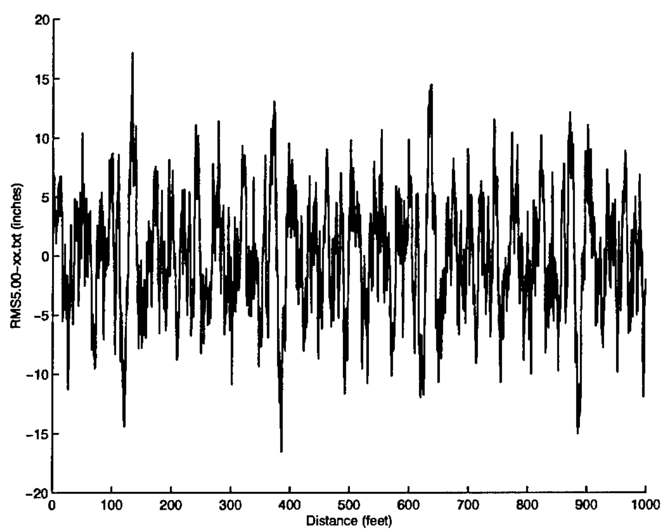

Figure 105 - Scaled 5.00" RMS

3.3 RMS Course Listing Example

RMS5.00-	1.218093	-0.734245	5.514481	7.332385	2.013225	5.642677	-0.637901	-2.777471	-4.362432	2.624828	3.909815	-6.333341	-7.403425	1.667419
01.txt	-0.983325	0.002283	4.427099	6.380244	2.268584	6.596493	1.510880	-3.637611	-3.229899	-0.265635	3.345447	-5.763155	-5.472385	1.955772
/magnitude,d	-1.980712	0.931356	4.998596	5.235779	2.323324	6.105487	1.336033	-5.853110	-2.673961	-3.318767	4.232356	-6.499456	-5.463148	1.446484
x in inches	-1.944331	-0.472792	5.786179	6.445378	0.420138	8.166833	0.808378	-5.650797	-1.816173	-3.320518	4.068756	-8.032326	-6.088272	1.239576
	-2.233902	-0.594984	6.362749	9.633328	-0.480711	7.079977	2.520398	-2.701498	-1.794227	-1.186380	0.098531	-8.017086	-7.202758	1.741907
4000,	-2.393708	-1.290645	6.813928	7.927866	0.343440	5.240821	2.569646	-5.034795	-3.884749	-2.533732	-1.947534	-6.554206	-6.745740	1.659139
3.000000	-2.423254	-2.805955	7.514844	8.149946	-0.616628	5.828401	3.454334	-5.357788	-3.381829	-4.183205	-4.140554	-3.901053	-3.830878	1.127577
	-2.972339	-1.797762	7.424133	9.518765	-1.294620	5.172338	4.657194	-4.737441	-2.959174	-3.724572	-4.670261	-1.076538	-2.299082	1.804318
1.106454	-4.239255	-4.283610	7.799425	8.773870	0.406534	2.470246	5.431590	-5.492590	-1.224879	-1.535075	-4.687024	1.786929	-1.877482	1.745477
1.699111	-4.291829	-5.084014	6.931020	10.987890	1.416479	0.134906	5.301497	-4.590536	-0.007392	-1.164336	-4.839762	2.251142	-2.534675	3.404248
4.480530	-3.244792	-6.550317	8.402907	10.927617	2.134897	-1.735384	2.360488	-4.282752	2.659954	-0.221760	-4.559396	2.931140	-3.311299	3.137958
4.536882	-4.643449	-7.939657	8.451157	12.116002	1.232372	-0.215770	1.002372	-2.711306	3.665678	-0.897043	-2.292717	3.491483	-3.800252	4.364720
4.798883	-4.074436	-5.810707	7.805272	13.146028	1.082094	-1.448553	2.674105	-2.718176	4.104417	-1.005621	-2.437960	3.520156	-4.507172	4.862893
4.353879	-4.462690	-6.300547	7.957005	13.519191	-1.206025	-0.209765	3.813537	-4.791036	1.747448	-1.241701	-3.599292	3.210716	-6.043896	5.686219
4.490341	-5.765694	-5.691117	8.535547	13.568297	-0.932410	0.903626	0.349904	-5.724641	0.474094	-1.812795	-4.521802	1.730841	-4.168450	5.340269
6.713574	-3.486668	-4.937887	8.609987	13.687142	-1.838911	3.359048	1.386170	-3.875455	0.143024	-1.806120	-5.489776	1.595334	-4.422205	7.624617
6.079264	-4.240444	-5.884863	8.681819	14.564068	-2.421873	3.670537	2.643335	-2.205391	0.898653	-1.470558	-4.419319	3.053036	-4.462694	7.235179
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3.550467	-3.080462	-6.316228	4.485317	14.701029	-3.096924	1.815674	-0.565466	-2.538715	-0.776313	0.293586	-6.057454	4.608038	-5.636799	8.681644
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2.519768	4.836499	-5.801977	0.888289	9.719497	-1.731272	4.598678	-6.095410	-5.265461	-3.733852	-4.216590	-0.433191	3.228420	3.788531	8.142156
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3.181528	4.613954	-6.358565	-6.396404	5.269724	6.683068	-1.018252	-5.164127	6.853668	-8.873378	-5.031810	10.391785	4.915890	1.214967	0.483114
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